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# Micro-pumped cooling loop to standardize micro-sat thermal control

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**Abstract**

With the miniaturization of space-borne sensors, more powerful payloads are anticipated to be used in small satellites. Therefore, new thermal concepts are required to cope with the increasing thermal dissipation and address the short development time available between customer demand and launch.
Compared to standard spacecraft thermal design three requirements become design drivers:

- Design flexibility for late orbit parameter changes
- Short development and MAI time
- Heat switch function to reduce heater power during eclipses

This paper presents a new thermal control concept to standardize small satellites with power dissipation problems.

First an inventory is made of the micro-satellite size for which thermal problems can arise. Subsequently it is explained why a heat switch function should be a key part of a micro-satellite thermal concept.

Two NLR thermal concepts are introduced with the focus on the micro-pumped cooling loop. This new thermal design concept is a small pumped loop. The heart of the system is the multi-parallel micro-pump as developed by the Netherlands aerospace centre (NLR). This pump concept provides a low mass pumped solution with high reliability. The article describes the concept of the loop and the pump in detail. Then, the advantages and drawbacks of the system are elucidated by comparison with conventional thermal design solutions with focus on the above mentioned design drivers.

The paper concludes with the development status, the further development plan of the micro-pumped loop and expected market demands for which the micro-pumped loop is a suitable solution.

**Keywords:** Thermal control, Mechanically Pumped Loops, Micro-pump, Heat Switch

**Symbols**

| | | |
|---|---|---|
| $M_{SC}$: | Spacecraft mass | [kg] |
| $P_{Sat}$: | Satellite power | [W] |

**Acronyms/Abbreviations**

| | |
|---|---|
| P/L: | PayLoad |
| S/C: | SpaceCraft |
| MPL: | Mechanically Pumped Loop |
| MPMP: | Multi-Parallel Micro-Pump |

## 1. Introduction

With the introduction of commercial swarms of satellites standardisation of satellite subsystems and components becomes a critical requirement for success.

For thermal subsystems design flexibility for late orbit parameter changes are also of key importance. This flexibility is needed to allow for a quick response to market demands of swarm customers.

The short thermal subsystem development time means there is no longer time for extensive thermal analyses to verify whether the swarm satellites survive the worst case conditions of all orbits involved. This makes passive thermal control solutions less attractive as they require a full set of thermal analyses.

Therefore thermal designs with (simple) active control become beneficial as they allow the thermal S/C designer to take control in extreme conditions. In large S/C's which in most cases have a cold-biased thermal radiator and a surplus in power, active control is normally implemented by survival heaters. For small satellites however, power is scarce and active control with heaters is undesirable as it reduces the S/C operational window. The preferred solution is to switch off radiators to keep the S/C above their low temperature limits in cold extremes.

This paper presents a new thermal control concept to standardize small satellites with power dissipation problems including a heat switch function.
First an inventory is made of the micro-satellite size for which thermal problems can arise.

## 2. Power trend of nano- to mini-satellites

For small nano-satellites no thermal control problems occur as the power generated by the solar cells is too low. Thermal design for small nano-satellite is therefore limited to thermal insulation, smart positioning of heat dissipating elements and local heat spreading to avoid peak temperatures. For such small satellites no thermal control concept is required. By increasing size the power also increases to a level where thermal problems occur.

In Figure 1 the power trend versus satellite size is shown.

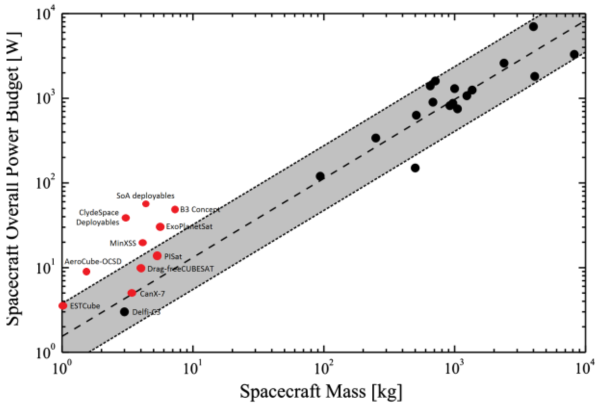


**Figure 1: Mass versus power trend line for satellites (modified by including data of state-of-the-art CubeSat [1], [2])**

Roughly for satellites with 20 Watt power or more thermal control problems are possible.

$$M_{SC} := \left(0.649 P_{sat}\right)^{1.07204} \quad (1)$$

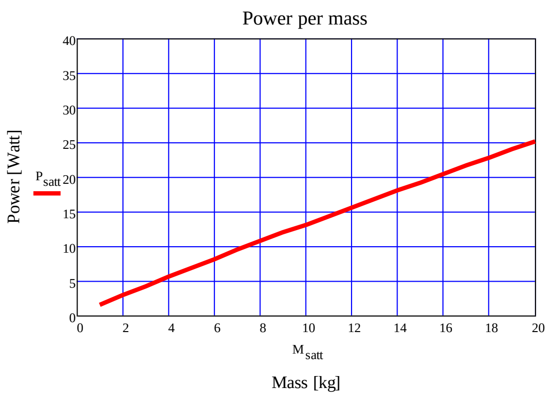


**Figure 2: Power as function of satellite mass**

This trend is shown in Figure 2. To get an idea of which CubeSat size this is plotted Figure 3 based on an average of 1.33kg per unit.

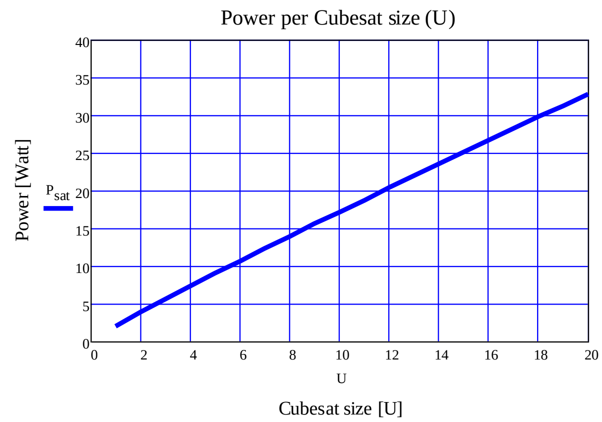


**Figure 3: Power as function of CubeSat size**

Derived from [1] and Figure 1 one can calculate the satellite mass as function of satellite power by equation 1. As thermal problems are not expected below 20 Watts, it can be stated that S/C of masses roughly below 16 kg no thermal concept is required based on the mass versus power trend line. However for small satellites the trend is different. This is illustrated by the red dots in Figure 1 [2]. Due to the demand for more functionality more power is generated by adding deployable solar panels to supply the payloads. This means that also for small (4-16kg) platforms thermal problems can occur when additional power is created by deployable solar panels.

Translated into the satellite classifications this means that until the size of pico-satellites a thermal concept is obsolete. A general thermal concept starts to be interesting for microsatellites and the high-end of nanosatellites with additional deployable solar panels. This is summarised in Table 1.

| Satellite Classification | Mass range | CubeSat size | Potential severity of thermal challenges | Remarks |
|---|---|---|---|---|
| Femto-satellite | (0.01–0.1 kg) | | | No power to create thermal problems |
| Pico-satellite | (0.1–1 kg) | | | No power to create thermal problems |
| Nano-satellite | (1–10 kg) | 1U-8U | | |
| Micro-satellite | (10–100 kg) | >8U | | |
| Mini-satellite | (100–500 kg) | | | |

**Table 1: Small satellite classifications and severity of thermal design challenges**

Main conclusion is that a thermal concept becomes relevant for satellites of 3U CubeSat size with large deployable solar panels or 8U without deployable solar panels. The thermal concept described below is therefore focussed for CubeSats of 5U and larger.

## 3. Requirements for a standardized thermal concept

For a heat switch concept standardized concept the requirements are listed below in order of relevance:

1. Low cost
2. Low volume (fit in 2 U)
3. Low power consumption (<3 Watt in all orbital cases)
4. Modular and flexible to integrate in CubeSats
5. Flexible to connect to P/L dissipative elements

The most important part of the concept is the heat switch function. This is due to the fact that small satellites are limited in power. In case the thermal radiators are designed for the hot case which means the radiator is so large that that the P/L can operate in all conditions. For operations and P/L output this is attractive. However, in cold cases the large radiator creates problems as the P/L will decrease in temperature very quickly and heater powers equal or larger than the P/L operational power are required to keep the P/L electronics within the survival temperature range. As cold cases normally occur in eclipse also a large battery is required. Due to this design challenge, radiators are normally down-sized with negative impact on the P/L operational window. With more and more demanding P/L´s this is one of the major issues to be solved by a standardized thermal solution for small spacecraft. Apart from a direct advantage for the P/L operational window, a heat switch function gives also more flexibility and increase the survivability during survival modes and unwanted tumbling of small satellites.
Furthermore the thermal concept needs to be low cost, small in volume, have low power consumption and must be modular and flexible to integrate in CubeSats.

## 4. Standardized thermal concepts

NLR investigates two potential options to cope with the upcoming thermal challenges of CubeSats with more advanced P/L's.

- A standardized solution based on water heat pipes
  - Heat switch function by freezing of the water in the heat pipes
- A standardized solution based on micro-pumped loop
  - Heat switch function by switching on/off the pump and thereby thermally disconnecting the radiators from the P/L.

The first option is investigated within a master thesis [2] and will only be described briefly. The second concept is a mini-pumped loop with the MPMP pump.

### 4.1 Thermal concept with standard copper water heat pipes

Water heat pipes potentially solve the thermal challenge of high performance CubeSat mission. This was researched during a master thesis [2] performed at NLR in co-operation with Innovative Solutions in Space (ISIS) and the Delft University of Technology. To meet the low-cost objective water-copper heat pipes were used. A corresponding benefit of using water heat pipes is the implicit heat switch function below 0 °C when water freezes.

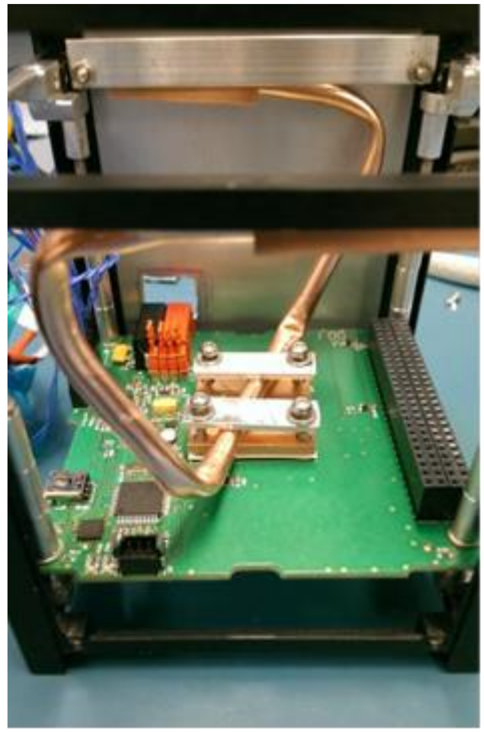

**Figure 4: Copper water heat pipes integrated in a 2U CubeSat for thermal testing**

Performance characterization, bending, and gravity-tilt tests were carried out. Transient start-up tests were performed and repetitive freeze/thaw cycles to observe the effect of the LEO environment on heat pipes. Finally, heat pipe integration in a CubeSat structure was done along with testing. Following from the different performance characterization tests and the heat pipe integration experiments it became clear that commercial water heat pipes can indeed solve for the thermal challenge that is upcoming in high performance CubeSat missions (see figure 3-1). The water heat pipe is able to passively transport the heat loads expected (up to 10 W) in the next-generation CubeSats, thereby keeping the heat source within its temperature limits due to the switch off below 0°C.
Heat pipe bending was found to have negligible influence on the heat pipe's performance, which gives flexibility in integration.
The critical aspect in integrating a heat pipe in CubeSat platforms is the connection with the P/L. The heat

transfer between source and sink is by clamping with implies pressed thermal contacts.
Conclusion is that heat pipe implementation is a feasible solution for single source hot spots. However for multiple heat sources heat pipe integration become troublesome so an alternative solution should be implemented such as a mini-pumped loop concept as described by the next section. It is advised to use heat pipe solutions as late add-on solution to solve ad-hoc thermal problems.

4.2 Mini-pumped loop concept

The second and proposed concept for standardization is to implement a mini-pumped two-phase loop in a CubeSat. The versatile two-phase pumped loop lay-out is shown in Figure 5.

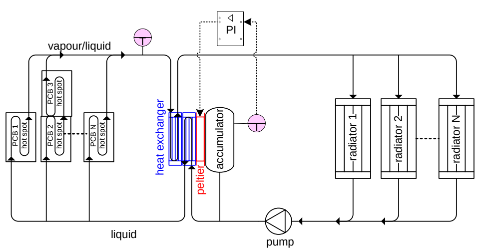


**Figure 5: Micro-pumped loop lay-out**

The loop transports the dissipated heat from hot spots to thermal radiators. Standard radiators with parallel channels can be used. The hot spot interface exists of small diameter tubing and is therefore flexible and suitable to be routed along many types of hot spots.

4.2.1 Pump

The heart of the system consists of the Multi-Parallel Micro-Pump (MPMP) as shown in Figure 6. This light-weight pump allows for the introduction of small pumped loops in space. The pump concept solves the pump reliability problem by using a large set (15-50) of parallel micro-pumps built in one unit, in which a single pump failure is no problem and even multiple pump failures will cause only graceful degradation.

**Figure 6: Multi-Parallel Micro-Pump (CAD drawing and picture)**

The pump is made of Titanium through Laser Additive Manufacturing and based on micro-pumps developed for the medical sector. Pump specifications for a 5 pump unit are:

- Flow rate 15 ml/min.
- Pressure head 50 mbar
- Mass 100 gr (excl. electronics)
- Average Power 600 mW

The pump is modular and can be extended to any required size. A completely welded prototype is currently under test at NLR.

4.2.2 Accumulator

Apart from the pump the accumulator is the most important component. By setting the accumulator temperature also the evaporation temperature of the evaporator/hot spot interfaces is controlled. A Peltier is used to control the temperature of the accumulator. The Peltier uses the heat exchanger as heat sink or heat source. The accumulator for a 60 W P/L power has a volume of ~20ml. It is built using 3D-printed titanium with a 3D-printed wick inside (simple mesh). A top view is shown in Figure 7.

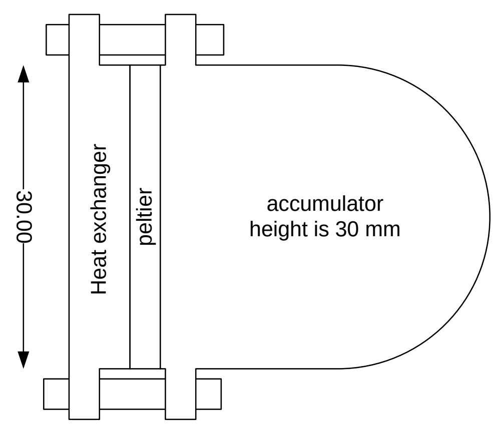


**Figure 7: Top view of the accumulator**

4.2.3 Heat Exchanger

The heat exchanger has two functions:

- Pre-heat the cold liquid prior to entering the evaporator P/L zone
- Heat sink for the accumulator Peltier temperature control

The pre-heat function is beneficial for start-up as it avoids the P/L to cool down in case the P/L is still off. The heat exchanger will be built using 3D-printed titanium. Inside the titanium heat exchanger are two layers of channels. Figure 8 and Figure 9 show a CAD drawing and a photo of a heat exchanger that was printed for a different project.

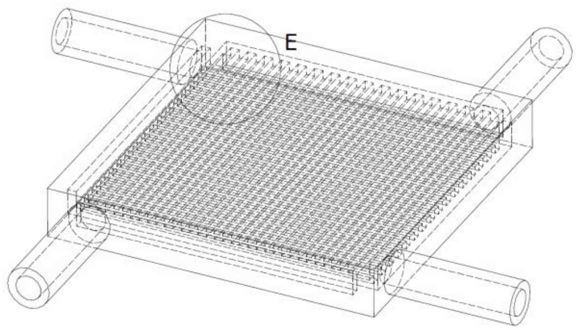


**Figure 8: CAD drawing heat exchanger**

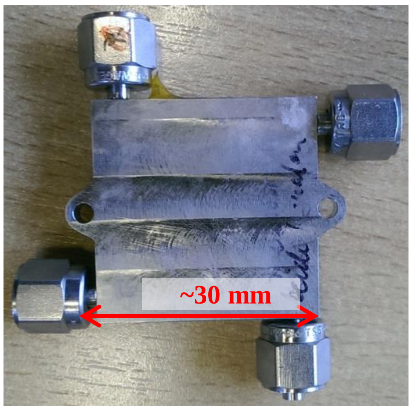


**Figure 9: Picture of the printed heat exchanger**

4.2.4 Loop Control

The proposed loop control is simple. The accumulator is controlled at a fixed set-point of +35 °C and is kept at that set-point with a PI –control based on temperature. In case the P/L is switched on upto the maximum (60-100%) the liquid will be raised to accumulator set-point. The liquid will then start evaporating increasing the heat transport capacity to the maximum of the system. This gives the opportunity to transport P/L powers upto 60 Watt to the radiators. For low P/L powers (20% to 60%) the P/L heat is not large enough to increase the temperature to the saturation. The loop will then operate as a single-phase pumped loop with a temperature varying roughly between 0 °C and +35°C. For lower P/L powers there is the risk that the P/L temperatures will decrease below the lower survival temperature of the P/L and therefore the pump should be switched off. This can be done automatically with a P/L switch-off.

4.2.5 Development status and development steps

The miniaturisation of the loop components has partly been performed in the framework of the European FP7 project TOICA study for aircraft avionics cooling, resulting in a micro-pumped loop on card level as shown in Figure 10.

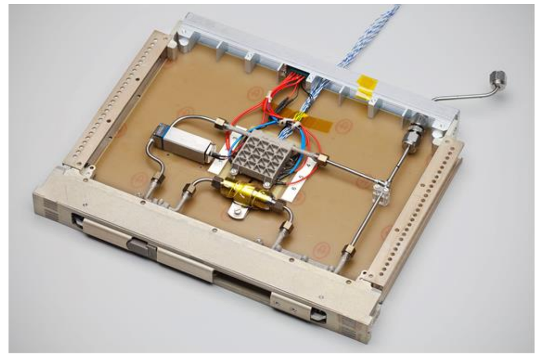

**Figure 10: Miniaturised two-phase loop on electronic card level**

Several components like the evaporator heat exchanger on top of the electronics, and the heat exchangers with the blade, were made with rapid manufacturing techniques (Selective Laser Melting SLM). The two-phase pumped TOICA loop is still equipped with a commercial pump. NLR developed also a software tool for transient two-phase systems.

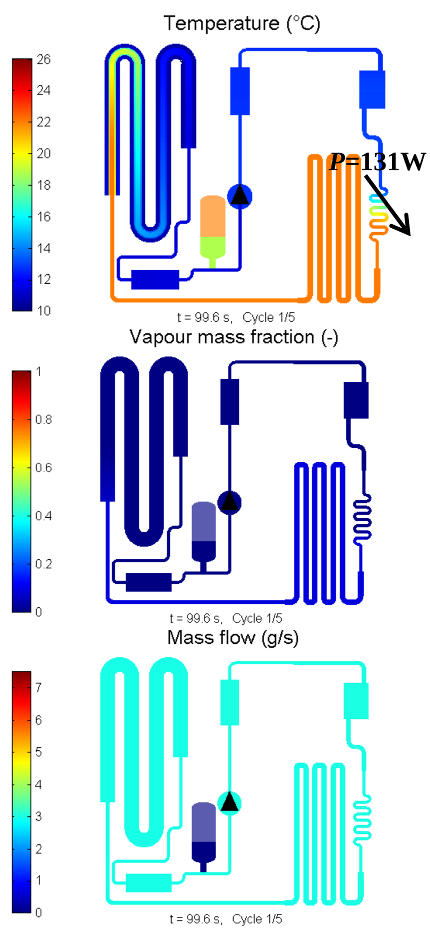


**Figure 11: NLR Simulation tool results showing temperature, vapor mass fraction, and mass flow transients**

This tool numerically solves the one-dimensional time-dependent compressible Navier-Stokes equations, and includes the thermal masses of all the components. The tool has been used for different projects, and the numerical results show an excellent agreement with experiments. This tool can be used to rapidly verify the operational performance of the loop in orbital conditions. Some results are shown in Figure 11.

The full metal Multi-Parallel Micro-Pump (MPMP) is also manufactured with SLM techniques and a 6 parallel pump prototype is currently under test. The pump runs with commercial electronics. NLR plans to develop full space qualified pump and loop control electronics for long life duration space missions (>3 years) and a commercial ruggedized electronics version for short life time and low cost missions.

## 4. Modularity and standardization

The proposed two-phase mini-pumped loop can be easily standardized. Depending on the P/L dissipation the number of radiators can be varied. A standardized package will consists of:

- one 1U or standard cube with pump accumulator, heat exchanger and loop control implemented
- flexible metal tubes for the connection with the P/L and radiators
- standardized P/L interfaces to assure a low · T between loop and P/L
- standard radiators 0.1 x 0.1 m2 to be located on customers preferred locations (see Figure 5)

Furthermore standard filling equipment can be designed and made available for rent or on-site support by NLR/ISIS. Also a standard thermal simulation tool can be made to verify the performance in specific orbits.

## 5. Modularity and standardization

A standardized thermal concept is proposed based on a two-phase mini-pumped loop. The system has a heat switch function and gives the possibility to cool P/L's with multiple hot spots. The multi-parallel micro pump concept uses a large set (15-50) of micro-pumps and solving the single-point-of-failure drawback of ordinary micro-pumps. The system is extremely flexible and versatile to cover thermal control problems from 3U to 16U CubeSats.

## 6. Conclusions

A standardized thermal concept is proposed based on a two-phase mini-pumped loop. The system has a heat switch function and gives the possibility to cool P/L's with multiple hot spots. The multi-parallel micro pump concept uses a large set (15-50) of micro-pumps and solving the single-point-of-failure drawback of ordinary micro-pumps. The system is extremely flexible and versatile to cover thermal control problems from 3U to 16U CubeSats. It is also applicable for series production for satellite swarms, especially for direct response missions for disaster monitoring or to support military reaction forces.

## Acknowledgements

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