Mini Mechanically Pumped Loop Modelling and Design for standardized CubeSat thermal control

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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 the negative effects. This paper presents a new thermal control concept to thermally standardize small satellites with power dissipation problems and making them thermally independent of their orbits.
This new thermal design concept is a mini Mechanically Pumped Loop (MPL). The design of the mini-MPL takes into account the requirements imposed by CubeSats and their subsystems, thereby ensuring its compatibility with small satellites and a variety of missions. The heart of the system is the multi-parallel micro-pump (MPMP) as developed by the Netherlands Aerospace Centre (NLR). This pump concept provides a low mass MPL solution with high reliability. Subsequently, the article describes the concept of the loop and pump and micro-pump test results are presented. The Mini-MPL is also modelled in Matlab to support MPL system design trade-offs. The model is described and modelling results are presented and included in the elaborate working fluid selection given. Finally, the advantages and drawbacks of the system are elucidated by comparison with conventional thermal design options. The paper concludes with an outlook on further development and mini-MPL applications.

Nomenclature

ρ	=	Fluid density (kg/m^3)
μ	=	Dynamic viscosity (N/m^2 s or kg/(ms))
σ	=	Stefan Boltzmann Coefficient
c_p	=	Specific heat capacity (J/(kg K))
d	=	Inner diameter tube (m)
f	=	Friction factor(-)
F_v	=	View factor (-)
h_{lv}	=	Specific latent heat of vaporization (J/kg)

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h = Specific enthalpy (J/kg)
L = Tubing length in the mini-MPL (m)
$\dot{m}$ = Mass flow (kg/s)
P = Power (W)
Q = Dissipated or radiated power (W)
p = pressure (N/m^2)
Re = Reynolds number (-)
T = Temperature (K)
v = Fluid velocity (m/s)

I. Introduction

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

To get an idea the of the power available on Cubesats, the power versus mass trend is shown in

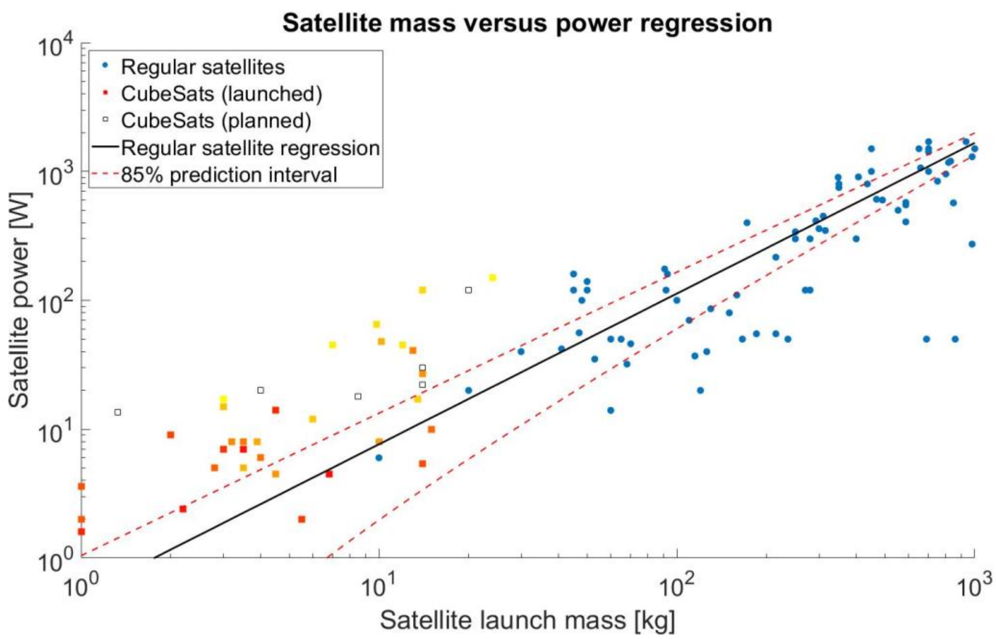


Figure 1. Mass versus power trend line for satellites (modified by including data of state-of-the-art CubeSat [1, 2]).

With the increasing power of Cubesats also thermal subsystems become also relevant for standardization.

Figure 1. Thermal problems will only occur for Cubesats with a significant amount of power. It is assumed that above 20 Watts the Cubesats can create thermal problems which require a Thermal Control System (TCS). 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 as summarized 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 Control System (TCS) 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 focused for CubeSats of 6U and larger [12].
At present, there is no active Thermal Control System (TCS) available for Cubesats and small sats (<100 kg), and thermal issues are resolved using passive means (radiation and to some extent heat pipes). However, as these satellites evolve, grow in size and/or become more capable, these passive means of thermal control no longer suffice, and an advanced TCS is required. In itself, such a TCS is also an enabler of new missions and capabilities, meeting the market trend:

- Larger Cubesats (> 12 U / 10 kg):
    - in particular for communication purposes (having high heat throughput);
    - with unfavorable distribution of heat source and sink
- The advent of deployable solar arrays on CubeSats, increasing their possible power consumption

More specific it is expected [10] that Advanced Thermal Control Systems (TCS) for CubeSats are already relevant for missions which have:

a) Electric propulsion;
b) High power RF payloads, such as radars;
c) High power transceivers for communication with Earth or Inter satellite links
d) Interplanetary missions with tight power constraints, where heat switching capabilities will reduce the heater requirement.

II. Requirements for a standardized thermal control system for CubeSats

Prior to the development of a standardized thermal concept a list of requirements was deduced. The key requirements for a CubeSat TCS are listed here:

- Low cost
- Low volume (fit in 1U)
- Low power consumption (<3 Watt in all orbital cases)
- Heat removal capability of 20-100W
- Heat switch capability to minimize heater power during eclipses
- Modular and flexible to integrate in CubeSats
- Flexible to connect to P/L dissipative elements

As for all subsystems also the TCS needs to be low cost, small in volume, have low power consumption and must be modular and flexible to integrate in CubeSats. An additional requirement important for CubeSat 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.

III. Mini-Mechanically Pumped Loop concept

The technology presented here is an advanced thermal control system providing the following performance/functionality:

- Heat removal capability: at least 20 W;
- CubeSat standards compatible, stowed volume < 1U;
- Heat switch function to minimize heater power in eclipses;
- Flexibility in platform thermal design and component distribution;
- Scalable to higher power dissipations (≤ 200 W);

- Flexible tubing allows mechanically decoupling of P/L and frame reducing the stresses on PCB components during launch

The base of the technology is the Multi-Parallel Micro-Pumped one-phase Loop (MPMPL) developed at NLR. This technology is currently at TRL 3.

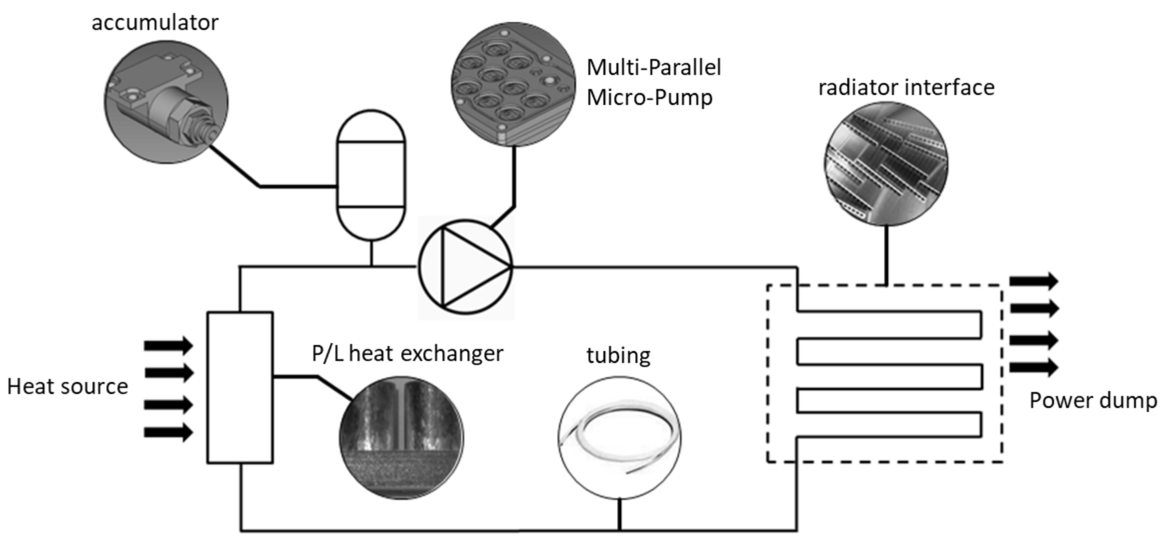


Figure 2 1: Mini-MPL Schematic

The mini-MPL transports dissipated heat from hot spots to thermal radiators. The loop is shown in Figure 2 1. The liquid is transported by the pump via a heat exchanger to the PCB (Printed Circuit Boards) hot spots, where the liquid collects the heat and cools the hot spots. The liquid flows back via the thermal radiators where the heat is radiated into deep space. The hot spot interface is connected with small diameter tubing and is therefore flexible and suitable to be routed along many types of hot spots. An accumulator allows for the volume changes of the liquid which can be large due to the large temperature variations in space.

A. Multi-Parallel Micro-pump

The heart of the mini-MPL is a multi-parallel-micro-pump and creates flow by 10-30 pumps in parallel. This design avoids the single-point of failure of a pumped loop. If one pump fails, still n-1 pumps are left to provide flow, which drops relatively to (n-1)/n fraction of the original flow. The first prototype of the multi-parallel-micro-pump is shown in Figure 2.

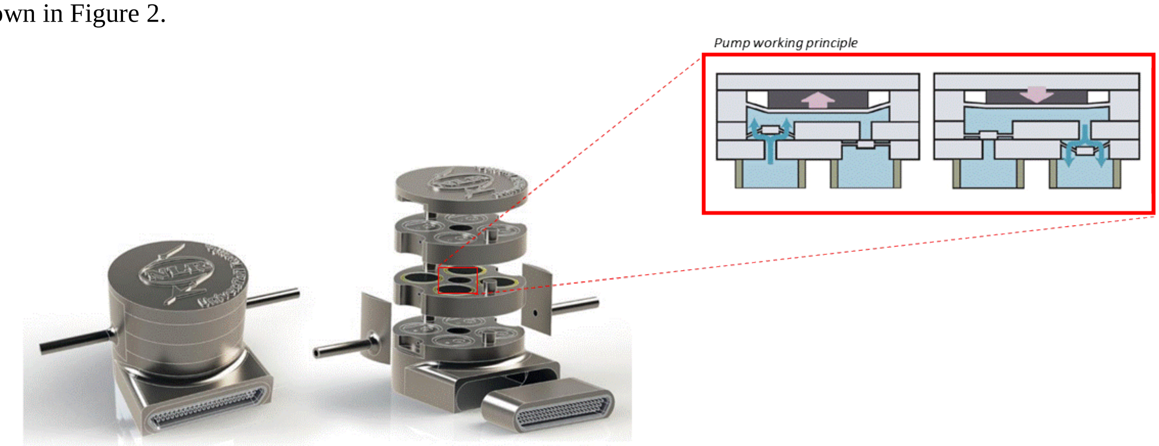


Figure 2: Multi-parallel-micro-pump (first prototype)

The single micro-pumps used as building blocks are piezo-driven displacement pumps with passive micro-valves. To better fit with the CubeSat modular set-up with mainly PCB's a second more flat design is made. This has the additional advantage that of lower static pressure differences between pump and therefore a performance which is more equivalent with micro-g operations. The pump will be metal printed in Titanium and will be hermitically sealed to the outside by laser welding.

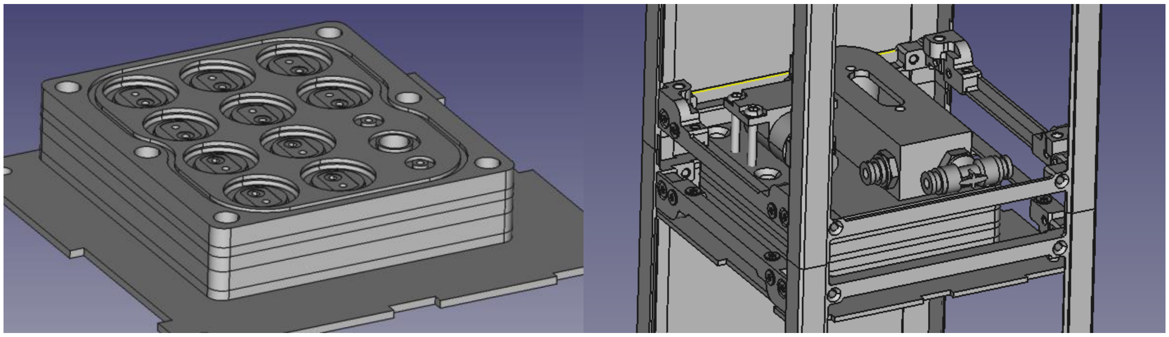


Figure 3: Multi-parallel-micro-pump, left: MPMP pump design, right: Implemented in a CubeSat

Also the valve design has been investigated and optimised to improve the MPMP robustness and performance. A typical pump curve for a single micro-pump with a 10 μm valve is given below.

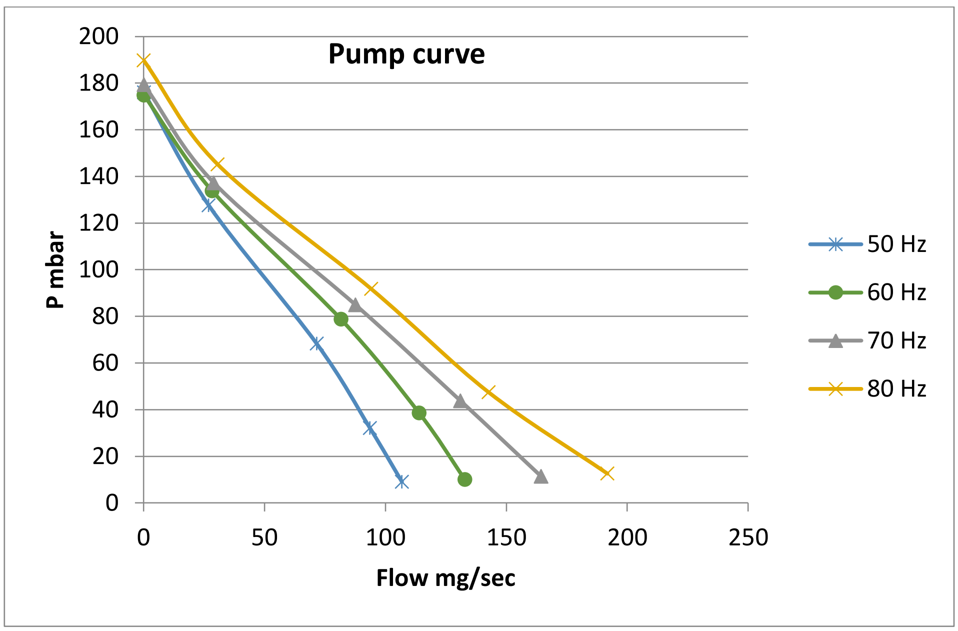


Figure 4: Micro-pump curve for a 10 μm thick valve with several piezo frequencies

B. Accumulator

Although the mini-MPL is a single-phase loop, the accumulator used is a two-phase accumulator. The system pressure is maintained by keeping the accumulator above a defined saturation temperature. This concept is more robust for launch vibrations and it allows for future upgrades to mini two-phase MPL's with much larger heat removal capabilities. The accumulator exists of a stainless steel container with an attached heater to keep the accumulator temperature above a threshold value. A filter is used for vapour blocking and liquid transport to the heater location.

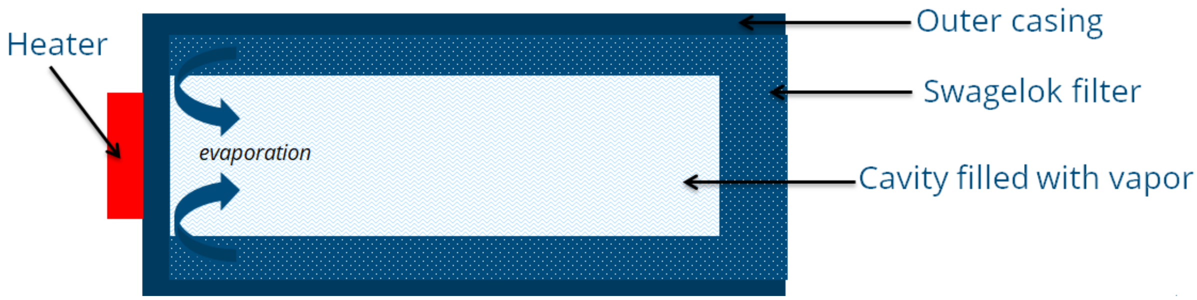


Figure 5: Two-phase accumulator concept design

C. Other loop components

The MPL further contains a payload heat exchanger which can be glued to hot spot components on PCB's in the CubeSat. Either procured parts or 3D printed Aluminum is foreseen. The mini-MPL electronics are limited to the MPMP Electronics of which a prototype is already made. Next step is an elegant COTS breadboard available in March 2020. The radiator interface selected is a multi-port extruded aluminum strip which can be connected to the outside of the CubeSat. This reduces the ΔT on the radiator side to the minimum possible. The selected flexible tubing to mechanically decouple the PCB hot spot and the CubeSat frame is fluoropolymer flexible tubing (PFA).

D. Mini-MPL single phase modelling

In order to analyze the mini-MPL's thermal performance the available NLR two-phase MPL software [13] is adapted for single-phase operation and to the smaller size of mini-MPL's. A typical model result is shown in Figure 6. Further model results are incorporated in the extensive working fluid selection described in section IV.

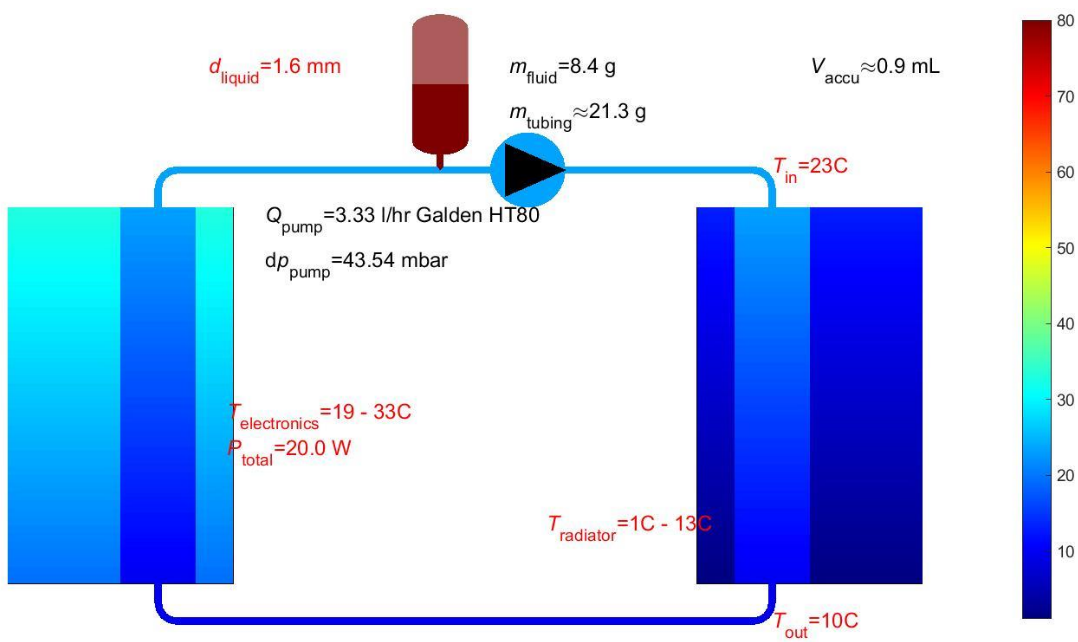


Figure 6: Single-phase mini-MPL model result with Galden HT80

IV. Mini-MPL working fluid selection

A working fluid is selected to fulfil the requirements of the preliminary system. First a pre-selection of working fluids is made based on working temperature range, pour point, critical temperature, saturation pressure at operating temperature, toxicity. The most important requirement is that the working fluid needs to be di-electric as the piezo connections are immersed in the liquid. The pre-selected working fluids are given in Table 2.

	T_{pour}	T_{boil}	T_{crit}	c_p	Density	μ	CTE
Fluid name	°C	°C	°C	J/kg K	kg/m^3	Pa*s	1/°C
R134a	-103	-25.9	374	1424	1207	1.95E-4	0.00323
R142B	-131	-8.9	410.3	1313	1112	2.30E-4	0.00231
NOVEC7000	-122	34	165	1300	1400	4.48E-4	0.0021
R141B	-103.5	32.2	477.5	1154	1234	4.09E-4	0.00157
Galden HT80	-110	85	>250	973	1690	9.56E-4	0.0012
Novec 7500	-100	128	261	1128	1614	1.24E-3	0.0013
Galden HT110	-110	110	>250	973	1710	1.32E-3	0.0012
Opteon SF10	-90	110	240	1000	1580	1.1E-3	0.0009

Table 2: Selected work fluid properties at 1 atm pressure and 25°C.

In order to rank the pre-selected working fluids figure of merits are used [11]. For MPL and mini-MPLs in particular, several criteria are important. For the following three aspects figures of Merit are defined for the MPL:

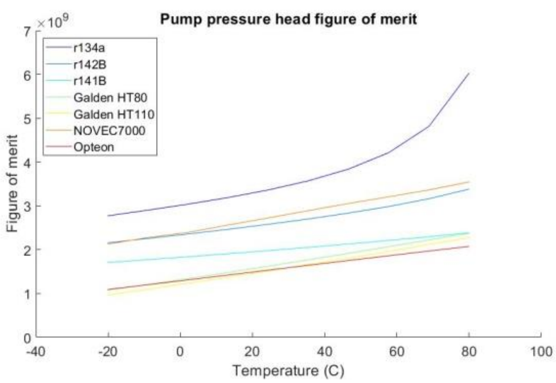
- Minimal pressure drop in the system
- Minimal required pump power
- Minimal size of the accumulator

The first two figures of merit are based on the pressure drop. The working fluid dependent properties on pressure drop are therefore isolated from the geometry dependent properties.

$$\Delta p \propto \overbrace{\left(\frac{\mu_l^{1/4}}{\rho_l C p^{7/4}} \right)}^{\text{fluid dependent}} \overbrace{\frac{L}{d^{19/4}}}^{\text{geometry dependent}} \left. \frac{P^{7/4}}{\Delta T^{7/4}} \right\} \text{Heat input and sensible temperature difference of the fluid} \quad (1)$$

Pressure head figure of merit

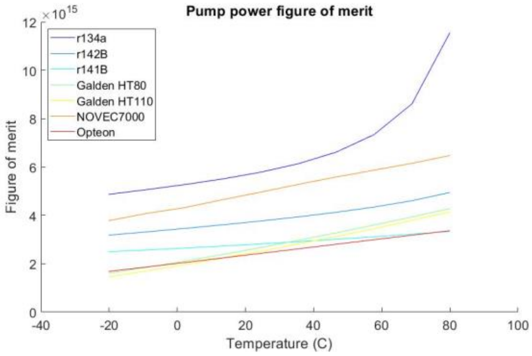
The working fluid figure of Merit for pressure head is then given by the inverse of the pressure drop term.



$$M_{\Delta p} = \frac{1}{\mu_l^{1/4} / (\rho_l c_p^{7/4})} \quad (2)$$

Pump power requirement figure of merit

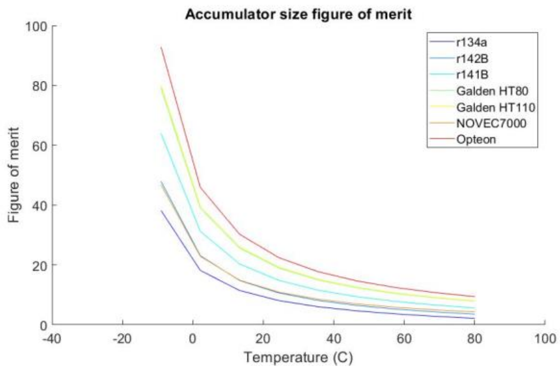
As power supply is limited on board any spacecraft, and especially CubeSats, it is important to take into account the power consumption of the pump in the mini-MPL. The figure is based on the product of the pressure drop and the volume flow required which is proportional with density and sensible heat.



$$M_{pump} = \frac{\rho_l c_p}{\mu_l^{1/4} \big/ (\rho_l c_p^{7/4})} \tag{3}$$

Accumulator size figure of merit

The third figure of merit is related to the accumulator in the MPL. It is beneficial for both volume and mass to have an accumulator that is as small as possible. The accumulator size is proportional to the expansion of the work fluid at minimum and the maximum operational temperature. The working fluid dependent part is present in the below figure of Merit.



$$M_{\text{acc}} = \frac{\rho_{Tmax}}{\rho_{Tmin} - \rho_{Tmax}} \tag{4}$$

Weighted figures of merit of pre-selected work fluids

The figures of merit have been calculated for all the pre-selected working fluids. The operating temperature range was set as -20°C to +80°C. The several aspects were given a weighing factor. The accumulator volume has the largest weighing factor. Pressure head and pump power are assumed to be of lower importance.

	$M_{\Delta p}$	M_{Pump}	M_{acc}	**Weighted Result**
Weights	1	2	4	
Fluid name				
R134a	1	1	1	1
R142B	0.78	0.65	1.64	1.73
NOVEC 7000	0.77	0.78	1.99	2.06
R141B	0.62	0.51	2.61	2.42
NOVEC 7500	0.51	0.53	3.32	2.97
Galden HT80	0.39	0.33	3.65	3.13
Galden HT110	0.42	0.4	3.7	3.20
Opteon SF10	0.39	0.35	4.36	3.71

Table 3: Figure of merits for pre-selected work fluids

The results show that R134a is ranked lowest. This is expected as the CTE of R134a is very large. Best rated liquids only based on figures of Merit are Opteon SF10 and Galden HT110 and HT80.

A. System analysis

In addition to the figures of merit a detailed analysis is done by performing full system calculations on a simplified MPL loop. The analysis is performed for each of the pre-selected working fluids. The following aspects are included in the analyses:

- Maximum tube length with given pump head
- Required pump power
- ΔT at the nominal heat load
- Required radiator area
- Accumulator volume
- Operating pressure
- Heat transfer coefficient (ΔT from tube to wall)

The maximum tube length can be calculated when the maximum pump pressure head is known:

$$L_{\max} = 2\frac{\Delta p d}{f_{\mathrm{l}}\rho_{\mathrm{l}}v^2} \qquad \text{with} \qquad f_{\mathrm{l}} = \frac{0.3164}{\mathrm{Re}_{\mathrm{l}}^{0.25}} \tag{5}$$

The required pump power is given by:

$$\mathrm{P}_{\mathrm{pump}} = \frac{\Delta \mathrm{p}\Phi}{\eta_{\mathrm{pump}}} = \frac{\Delta \mathrm{p}\dot{m}}{\eta_{\mathrm{pump}}\,\rho_{\mathrm{l}}} \tag{6}$$

The ΔT at nominal heat load follows directly from the working fluid heat capacity;

$$\Delta T = \frac{Q}{\dot{m}c_p} \tag{7}$$

The required radiator area is directly related to this ΔT but is also calculated to verify the impact on the radiator design.

$$A_{rad} = \frac{Qmpl}{\epsilon\sigma(1-F_v)\left(T_{rad}^4 - T_{space}^4\right) + F_v Q_{ir}} \tag{8}$$

The accumulator volume depends on the Coefficient of Thermal Expansion (CTE) of the liquid and is for a single-phase MPL given by:

$$\frac{V_{\mathrm{acc}}}{V_{\mathrm{loop}}} = (T_{\max} - T_{\min}) * \mathrm{CTE} \tag{9}$$

The calculations are performed with the following assumptions:

- Pump
  A single NLR micro-pump has a capacity of 200 mg/s with a pressure head of 100mbar. Ten pumps in parallel are assumed with a total flow of 2 g/s and pressure head of 100 mbar. A conservative pump efficiency of 5% is assumed
- Heat removal capacity
  The required heat removal capacity is set to 100W.
- Radiator environment and properties
  A deep space temperature of 4 Kelvin is assumed. Additionally the temperature of the surface of the earth is estimated to be around 10°C. The radiators on the CubeSat are assumed to have an emissivity coefficient of 0.9. The heat absorbed from the sun is not taken into account.
- Tubing
  A tubing diameter of 3 mm is assumed.

The results as presented in Table 4 are colour coded; green indicates it is the best result and yellow indicates the second best. The colour orange indicates a possibly problematic result which could exclude the fluid from further evaluation.

	Max. L_{tube}	Req. Pump power	ΔT	T_{sat} at 1.5 bar	Operating pressure at 80 °C	V_{acc}/V_{loop}	Heat transfer
Fluid name	m	W	°C	°C	Bar	%	W/m^2K
R142B	20	0.35	39	2	13.8	8.6	236
R141B	19	0.32	44	44	4.2	6.7	190
R134A	23	0.32	36	-16	26.3	10.9	260
Galden HT80	20	0.24	52	97	0.94	6.1	102
Galden HT110	18	0.23	48	123	0.33	5.5	90
NOVEC 7000	21	0.28	39	48	4.1	7.8	172
NOVEC 7500	17	0.25	45	N/A	N/A	5.7	97
Opteon SF10	17	0.25	50	±150	0.35	5.0	95

Table 4: Cooling loop parameters for selected work fluids at 100W heat load without pre-heater with Tset=20°C.

All tube lengths are acceptable and therefore the pressure head is not a design driver. For the pump power the Galden fluids perform the best due to the large density and sensible heat values. The difference is however not large enough to discriminate between liquids. The ΔT which is related to both sensible heat and the heat transfer coefficient is a measure for how much heat can be collected before the maximum payload temperature is reached. R134a is performing best and the worst alternatives have a 15° C additional temperature rise. For small systems this value is not yet driving but for extensions in the future a low ΔT is preferred. As the system operates with a two-phase accumulator to pressurize the system the required saturation temperature for a 1.5 bar operating is presented. Preferred liquids have a saturation temperature above 20 °C but not exceeding 100 ° C. This excludes Galden HT110 and Opteon SF10.

Another real system driver is the operating pressure at 50 °C, this is the system pressure expected during operation. Pressures above 10 bars are excluded because of impact on mass and design flexibility. On the other hand pressures below 1 bar are also problematic during testing. Any leak results in air and water vapour in the system with potential detrimental effects on pump operation and fluid characteristic in case of a hygroscopic fluid. The best performing liquids are then R141b and NOVEC7000. For R134a and R142b the pressures are too high to be acceptable.

The main mass driver is the accumulator size. Opteon performs here best with Galden and Novec liquids as second best. Here R134a underperforms significantly which is the main reason R134a is not favourable for space applications.

The last aspect listed is the heat transfer coefficient. With the low power densities in CubeSats and the various new technologies of increasing heat transfer area at low cost by e.g. metal printing this aspect is less important than in larger TCS. Here R134a is outperforming all other fluids.

Based on the above results Galden HT80 is selected as preferred working fluid and used in the detailed design phase as baseline.

V. MPL comparison with conventional thermal solutions

The Mini-MPL is not the only thermal solution which can address the CubeSat thermal challenges. Also heat pipes (HPs), mini LHP's, Phase Change Materials (PCM) and thermal straps are potential solutions. The main advantages and drawbacks of these systems compared to the mini-MPL are given in Table 5.

Thermal solution	Comparison with mini-MPL	
	Advantages	**Drawbacks**
HP's	Simple, low cost, well-known, No active components	Inflexible and non-modular design Limited amount of hot spots can be addressed Rigid connection between PCB connection and CubeSat frame Low reliability of heat switch function
Mini-LHP's	No active components, well-known	Inflexible and non-modular design Limited amount of hot spots can be addressed No or heavy heat switch capability
PCM	No active components, low-cost, well-known,	Inflexible for late orbital changes Limited amount of hot spots can be addressed
Thermal straps	No active components, reliable, low cost	Low thermal performance

Table 5: Comparison between mini-MPL and alternative thermal control solutions for CubeSats

It follows that the main advantages of a mini-MPL are the flexibility and the modularity. The drawback is obviously the active nature of the mini-MPL. The reliability problem is however addressed well by the multi-parallel-micro-pump concept.

For CubeSat thermal subsystem design, flexibility is of key importance to allow for a quick response to market demands of swarm customers. The short development time implies 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. .

VI. Conclusion

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 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.

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