Valve-less Mechanically Pumped Fluid Loop (MPFL) using East and West Panels of a Large Telecommunication Satellite as Radiator

Presented at 45th International Conference on Environmental Systems (ICES) 2015, July 12-16th, Seattle, USA

Customer

National Aerospace Laboratory NLR

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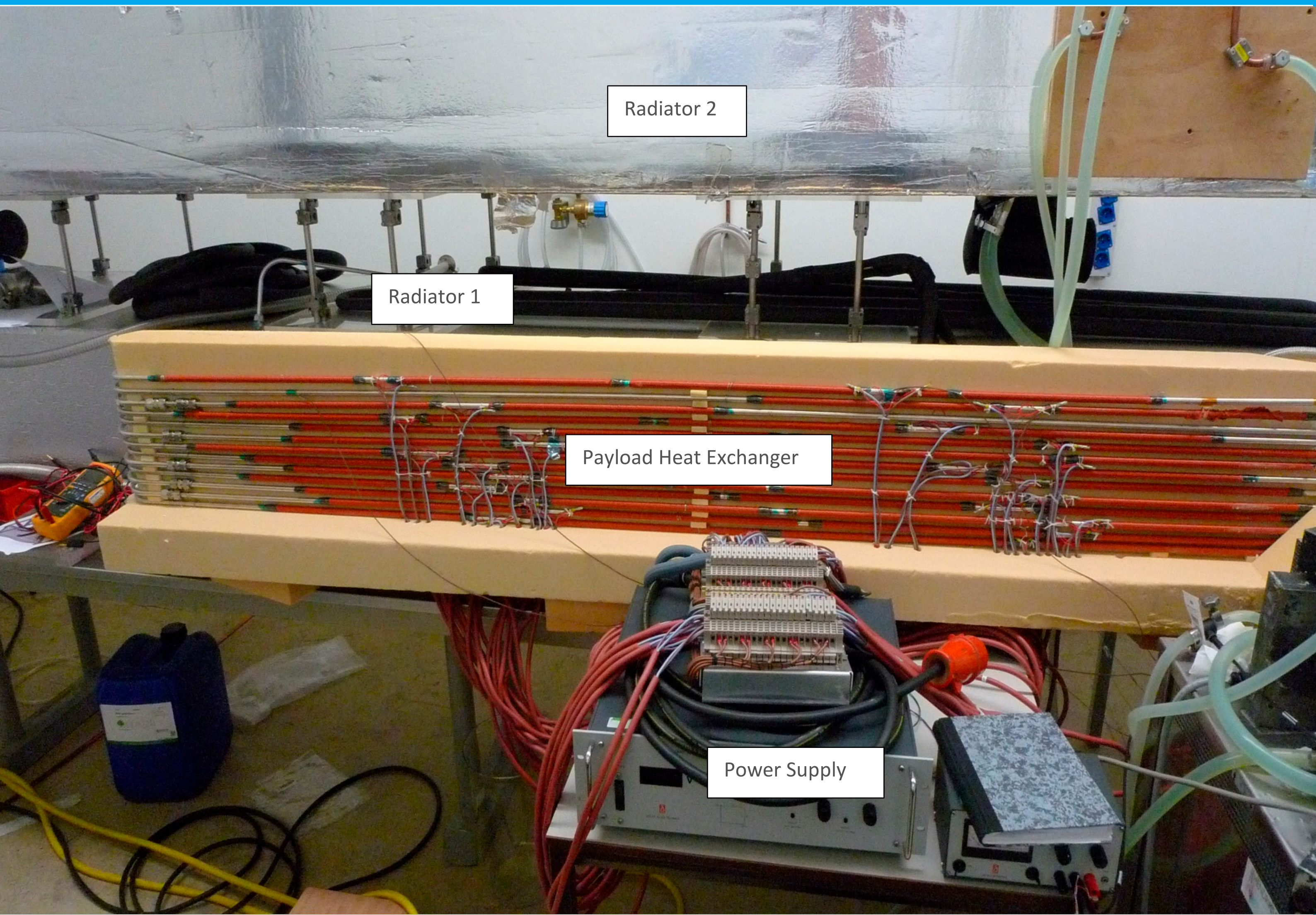

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Part of the full scale MPFL as tested in NLR laboratory with the Payload Heat Exchanger (PHX) with its insulation removed and two Radiators.

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EXECUTIVE SUMMARY

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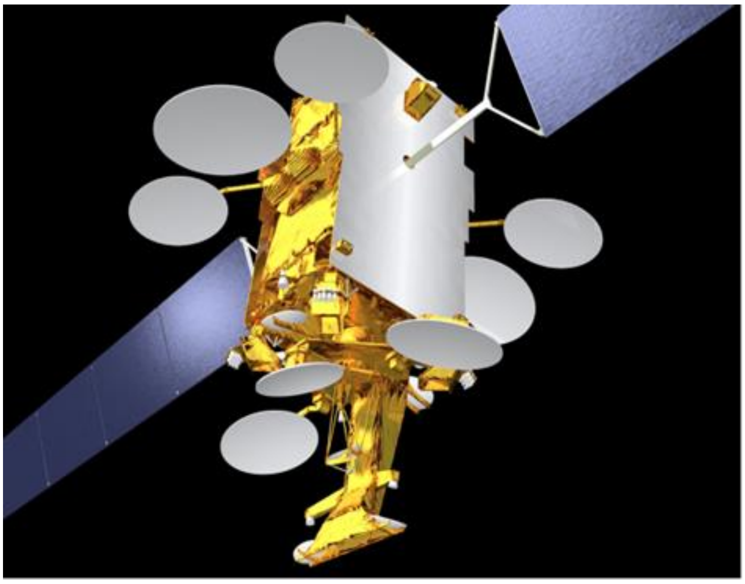

Artist impression of AlphaSat (ESA)

Problem area

For a decade development of a 3-6kW single phase Mechanically Pumped Fluid Loop (MPFL) for active cooling of large telecommunication platforms such AlphaSat is initiated and supported by ESA up to and laboratory demonstration of a full scale loop and (partial) qualification of the loop components such as a pump, bypass valve, pressure transducers and accumulator. Until recently application of MPFL has been postponed by satellite builders because, the performance of conventional thermal solutions such as heat-pipe-networks could be extended to their limits. MPFL makes a more compact design of the satellite structure possible with the heat dissipating transceivers located

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Knowledge area(s)
Space Applications

Descriptor(s)
Cooling System
Pumped Loop
Valve-Less
Communication Satellite
East-West Rediator

This report is based on a presentation held at the 45th International Conference on Environmental Systems, July 12-16, 2015, Bellevue, Washington.

on an internal structure instead of the conventional location on the side panels.

Description of work

An option discussed in this paper for application in large geostationary satellites is to install it as a secondary cooling system without valve on the E/W panels. E/W panels are currently hardly used for cooling because parts of the orbit time they are exposed to solar flux that reduces their efficiency. Since the E/W radiators are not exposed to solar flux at the same time and will not become hotter than about +7^{o}C, the E/W radiators are suitable for heat rejection. By arrangement of the payload loop in two sections in series with the East and West radiator a valve for controlling the flow is not needed.

Results and conclusions

A mathematical model of this valve-less MPFL configuration is constructed to predict the thermal/hydraulic performance and orbital temperature stability. Transient thermal analysis and laboratory tests with a full scale loop showed that -without valve- orbital temperature stability of the payload is in the range of ±5.5^{o}C, under variable load conditions. This can be improved by thermally crosslinking payload sections. A valve-less MPFL is therefore a recommended solution as (secondary) cooling system for large geostationary satellites allowing for more compact structural designs (or a higher power density), efficient use of the East/West radiator panels and improved system reliability.

Applicability

Mechanically Pumped Fluid Loops for space applications.

Valve-less Mechanically Pumped Fluid Loop (MPFL) using East and West Panels of a Large Telecommunication Satellite as Radiator

Presented at 45th International Conference on Environmental Systems (ICES) 2015, July 12-16th, Seattle, USA

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Summary

For a decade development of a 3-6kW single phase Mechanically Pumped Fluid Loop (MPFL) for active cooling of large telecommunication platforms such AlphaSat is initiated and supported by ESA up to and laboratory demonstration of a full scale loop and (partial) qualification of the loop components such as a pump, bypass valve, pressure transducers and accumulator. Until recently application of MPFL has been postponed by satellite builders because, the performance of conventional thermal solutions such as heat-pipe-networks could be extended to their limits. MPFL makes a more compact design of the satellite structure possible with the heat dissipating transceivers located on an internal structure instead of the conventional location on the side panels. Another option discussed in this paper for application in large geostationary satellites is to install it as a secondary cooling system without valve on the E/W panels. E/W panels are currently hardly used for cooling because parts of the orbit time they are exposed to solar flux that reduces their efficiency. Since the E/W radiators are not exposed to solar flux at the same time and will not become hotter than about +7^{o}C, the E/W radiators are suitable for heat rejection. By arrangement of the payload loop in two sections in series with the East and West radiator a valve for controlling the flow is not needed. A mathematical model of this valve-less MPFL configuration is constructed to predict the thermal/hydraulic performance and orbital temperature stability. Transient thermal analysis and laboratory tests with a full scale loop showed that -without valve- orbital temperature stability of the payload is in the range of ±5.5^{o}C, under variable load conditions. This can be improved by thermally crosslinking payload sections. A valve-less MPFL is therefore a recommended solution as (secondary) cooling system for large geostationary satellites allowing for more compact structural designs (or a higher power density), efficient use of the East/West radiator panels and improved system reliability.

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Content

Nomenclature

A	=	Surface area radiator	[m^2]
C_p	=	Specific heat capacity	[J/kg/K]
$\dot{m}$	=	Mass flow rate	[kg/hr]
ΔT	=	Temperature difference or gradient	[K]
P	=	Power or Heat load	[Watt]
ε	=	IR Emission coefficient	[-]
σ	=	Stefan–Boltzmann constant	[$5.67.10^{-8}$ $Wm^{-2}K^{-4}$]
α	=	Solar absorption	[-]

Abbreviations

BPA	Bypass Assembly
HCA	Heat Controlled Accumulator
gN_2	Gaseous Nitrogen
MB	Moog Bradford BV
MPFL	Mechanically Pumped Fluid Loop
NLR	National Aerospace Laboratory
OSR	Optical Solar Reflector
PA	Pump Assembly
PHX	Payload Heat Exchanger
RHX	Radiator Heat Exchanger
RT	RealTechnologie AG
3WV	3- Way-Valve

I. Introduction

With the growing heat dissipation of high performance electronics the demand for more efficient cooling systems for scientific and large telecommunication satellites is steadily increasing, up to a point that alternative cooling technologies such as one or two phase fluid loops could replace conventional (Loop) Heat Pipe systems. In 2004 ESA initiated the development of single phase 3kW Mechanically Pumped Fluid Loop (MPFL) for Alphabus[1, 2, 3]. See Figure 1. The MPFL development is performed under the ARTES-8 programme in a consortium with Moog Bradford Engineering BV (MB, The Netherlands) as prime contractor with the pump manufacture RealTechnologie AG (RT, Switzerland) and the National Aerospace Laboratory (NLR, The Netherlands) as subcontractors [1, 2, 3]

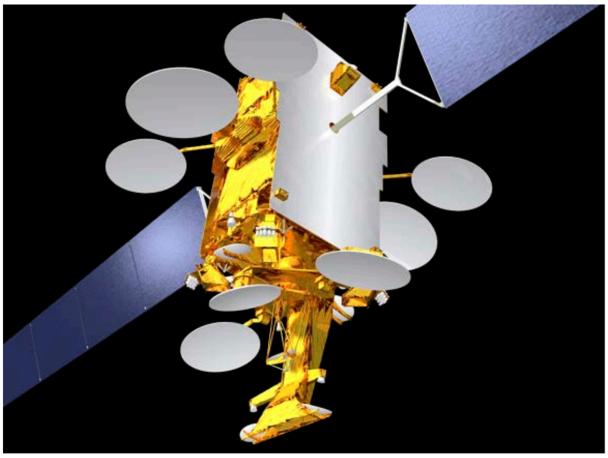
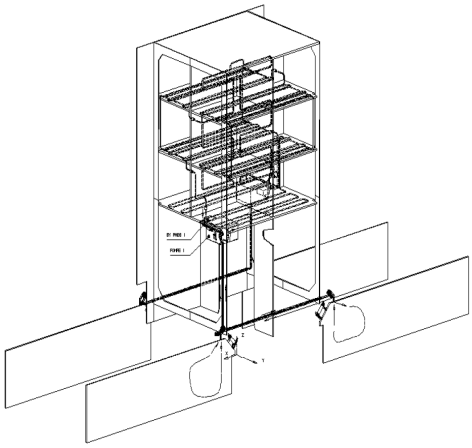

Figure 1 Envisaged application of MPFL in Alphabus (left), with deployable radiators (right)

MPFLs offer distinct advantages over conventional two-phase capillary pumped loops or heat pipe networks such as:

- Compact structural designs with less geometrical constraints on payload/external surface panels allowing heat dissipating equipment to be located anywhere within the satellite.
- Enhanced cooling performance by exploitation of addition (or deployable) radiator surfaces.
- Ease of integration with the satellite structure by application of simple tubing connections.
- Flexibility of ground test operations without restrictions related to orientation with respect to gravity.
- Simplified in orbit commissioning and start-up with respect to 2-phase systems.

Application of MPFLs has been successfully demonstrated for interplanetary missions e.g. Mars Pathfinder and the Mars Exploration Rovers[4,5].Implementation of a MPFL for these missions was necessitated by the combined envelope of temperature control requirements of the spacecraft during launch, cruise and Martian surface operations. Furthermore, in human spaceflight mechanically pumped loops have been employed (e.g. shuttle cargo bay, EVA-suits, etc.), and will be a required technology in future programs such as human-rated trans-lunar or interplanetary spacecraft and surface bases.

Despite the technical advances, commercial application of MPFLs has been discouraged by the non-existence of a dual-source for the pump assembly in Europe and orbital life time demonstration. Also MPFLs disruptive nature requires a re-design of the satellite structure and changes in AIT activities to obtain its full benefit. Market acceptance could be made possible by combining MPFL with conventional thermal control technologies rather than to replacing them. The valve-less MPFL as proposed in this paper offers such an add-on system on-top-of conventional thermal control, enhancing cooling performance by exploiting the East and West panels of geostationary satellites as additional radiator surfaces. The East and West panels are currently hardly used for cooling because they are exposed to solar radiation during large parts of the orbit.

In **Section II** the paper discusses the operating principle and design features of the 3kW MPFL developed for Alpabus. The valve-less design is introduced for enhanced payload cooling of geostationary satellites support by orbital thermal stability analysis in **Section III**. The paper with concludes in **Section IV** with test results obtained with the modified 'valve less' MPFL test-setup proving an excellent stability under varying load conditions.

II. Mechanically Pumped Fluid Loop

A. MPFL Operation Principle

The 3kW MPFL is a single phase fluid loop which operation (Figure 2) is based on the physical principle that heat (P) produced by the payload equipment is absorbed by a circulating fluid mass flow ($\dot{m}$). Due to the fluid heat capacity (C_p) its temperature rises (ΔT) according to $P = \dot{m} C_p \Delta T$ and lowers inside the radiator releasing heat into space closing the cycle. The fluid is circulated by a pump via tubing routed through the Payload Heat Exchanger (PHX) and the Radiator Heat Exchanger (RHX). For this example the Payload Heat Exchanger has two sections but it could be one or more sections. The 3kW MPFL design (right) has a single tube PHX (70m) and a RHX (90m) with four parallel branches to reduce the hydraulic resistance. For improved reliability the 3kW MPFL has two pumps in the Pump Assembly (PA) and two 3WVs in By-pass Assembly (BPA) that can be switched between the main and redundant components using internal valves. An accumulator is required to compensate for fluid expansion to prevent high system pressures.

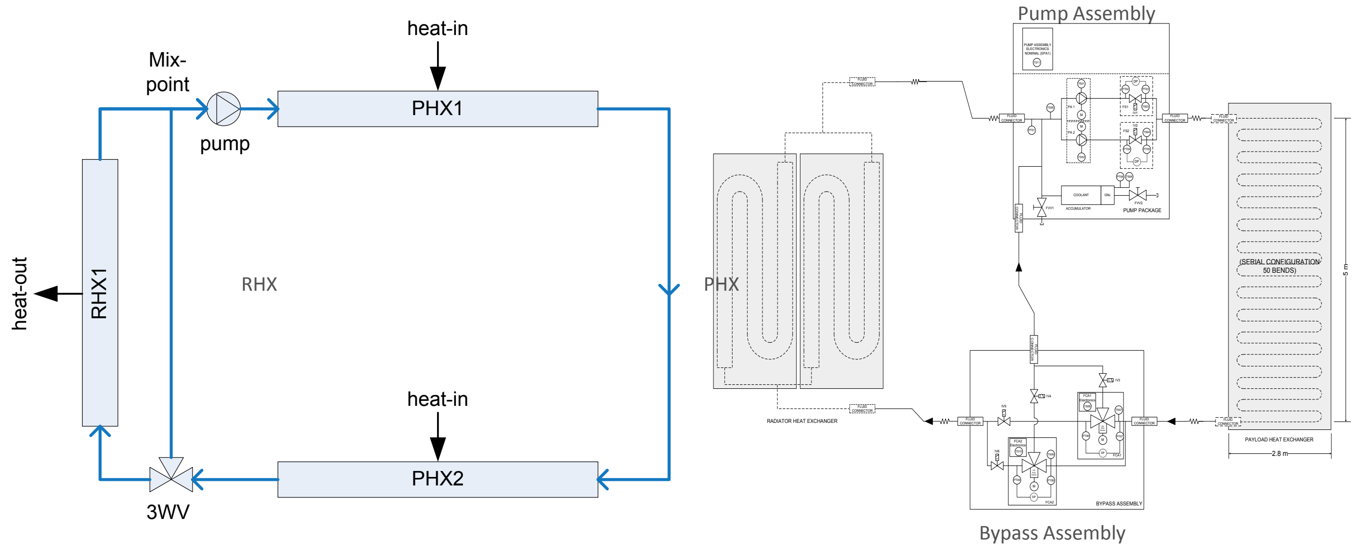

Figure 2 Operating principle by circulating single phase fluid using a pump (left) and 3kW MPF implementation with redundancy (right)

The accumulator volume is usually 20-30% of the total loop volume related to fluid expansion and the operational temperature range and to compensate minor fluid leakages. The accumulator (Figure 3) is a fluid container connected to the loop at the lowest pressure point i.e. the pump in-let. The system pressure is controlled with a metallic bellow or with a heater to prevent boiling of the fluid anywhere in the loop. For the bellow type accumulator, gN_2 is applied at the gas side to obtain a system pressure *above* the vapour pressure anywhere in the loop. For the HCA the system pressure *equals* the vapour pressure which is achieved by heating the fluid inside the accumulator *above* the maximum allowed fluid temperature anywhere in the loop. The Heat Controlled Accumulator (HCA) is under development at NLR with the advantage that it has no mechanical parts. The internal wick structure is required in a low gravity environment to prevent that vapour bubbles entering the liquid line.

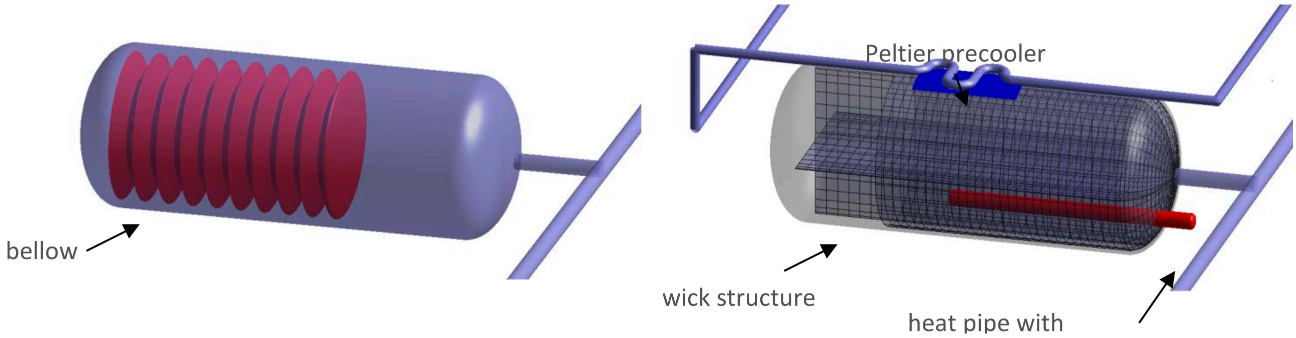

Figure 3 Accumulator Design (left) with Bellow (base-line MPFL) or (right) Heater Controlled (under development at NLR)

The "heart" of the 3kW MPFL is the RT pump which speed can be varied but for improved reliability operates at a nearly constant speed around 22.000 RPM. A Three-Way-Valve (3WV) regulates the fluid through the RHX (or bypass) between 0 and 100% and controls the heat rejection capacity of the radiator to deep space. The pump inlet temperature (mix-point) can be controlled with the 3WV to a set-point temperature between the operational limits. The function of the valve is that the hydraulic resistance of the loop remains nearly constant during operations thus minimizing pump speed variations and making a pump shut down for extremely cold environmental cases overdue. Another advantage of this arrangement is that the 3WV can be used as 'heat switch' during cold start-ups or payload failure cases with low loads by (partly) shutting down the radiator. Disadvantage is that the valve is an additional mechanical component that lowers the system reliability.

B. MPFL Working Point

Major engineering effort for designing MPFL applications is to define the systems 'working-point' matching the required fluid mass flow for the required heat transport capability at the allowed temperature gradient and the hydraulic resistance of the tubing (including bends and components) with the pump characteristics. Since the length of the loop is usually known by design this is done by sizing of the tubing. The loop minimum and maximum temperature levels are related to the load cases and the surface area of the radiator(s). The final design step is the size of the accumulator that is related to the total volume of the loop, the expansion of the fluid and the temperature range. The base-line fluid for MPFL selected after extensive investigation is Galden HT80® a PFPE (*Perfluoropolyether*) with a boiling point of 80°C at ambient pressure with excellent chemical, thermal and radiation stability. Galden HT80® is exempted from registration and evaluation within REACH.

C. Design features of the 3kW MPFL for Alphabus[1,2,3]

• Operational range	-20 °C to +80°C
• Non-operational	-100 °C to +100°C
• Tubing length	180m (70m PHX + 90m RHX + 20m transport lines)
• Tube inner diameter	8.3 mm (PHX, single tubing) + 4x4.3 mm (RHX, parallel tubing)
• Mix-point temperature	+10-50°C (30°C 'nominal' set-point)
• Working Fluid:	Galden HT80® (*Perfluorpolyether*, PFPE)
• Temperature gradient	ΔT=28°C @ 3000 W load
• Working-point pump	22.000 RPM (116 W)
• Pressure head	Δp=4.5 bar
• Mass flow rate	Φ_m=380 kg/hr (Φ_v=220 l/h)
• Accumulator size	2.1 litre
• Design life	15 years
• Total mass	45 Kg
○ Tubing	8 Kg
○ Fluid	12 Kg (loop volume is ≈ 8 litre)
○ Accumulator	4 Kg
○ Pump Assembly	11 Kg (two RT pumps for redundancy including valves & electronics):
○ Bypass Assembly	10 Kg (two 3WVs for redundancy including valves & electronics)

A full scale 3kW MPFL is since 2009 kept operational in NLR laboratory for testing purposes. See Figure 4.

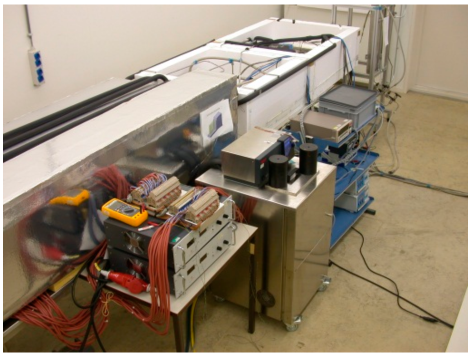

Figure 4 Full scale 3kW MPFL available at NLRs laboratory

D. MPFL Design Options

One of the options investigated is to implement MPFL as secondary or 'top' cooling system for additional cooling of a geostationary satellite in combination with conventional thermal control for an increased lifetime of the payload equipment. Additional cooling is achieved by using the East and West panels as radiators. This arrangement ensures that in case of loop failure because the payload temperature increases up to qualification level and the system is not lost. For emergency or low power cases of the payload below a threshold temperature of 20^{o}C it is recommended to switch off the pump while the payload temperature is regulated by conventional means of thermal control. Since this will only happen in rare occasions this hardly affects the reliability and life time of the pump.

The East and West side panels are normally not used for cooling because they are exposed to solar radiation during half of the 24 hours orbit. See Figure 5. The solar heat flux follows a sinusoidal curve (i.e. solar incident angle with respect to the surface normal) with a peak heat flux of 1400W/m^2 at 90 degrees solar incident angle. The other half of the orbit the panels view deep space with a 12 hours shift between them.

Analysis shows that the maximum heat rejection capacity of the East and West panels covered with OSR is about 440W/m^2 (@40^{o}C, α=0.22, ε=0.8) when viewing deep space at 4K and approaches to zero when exposed to 90 degrees solar incident angle. The peak radiator temperature is influenced by the optical ratio (α/ε=0.275) of the applied OSR over life. For this example, a conductively decoupled radiator with α/ε=0.275, its temperature rises up to about +14^{o}C in full sun.

The obvious design idea (Figure 5) was to replace the bypass with the second radiator (RHX2) and use the 3WV to direct the fluid between the East (RHX1) and West (RHX2) panels every 12 hours.

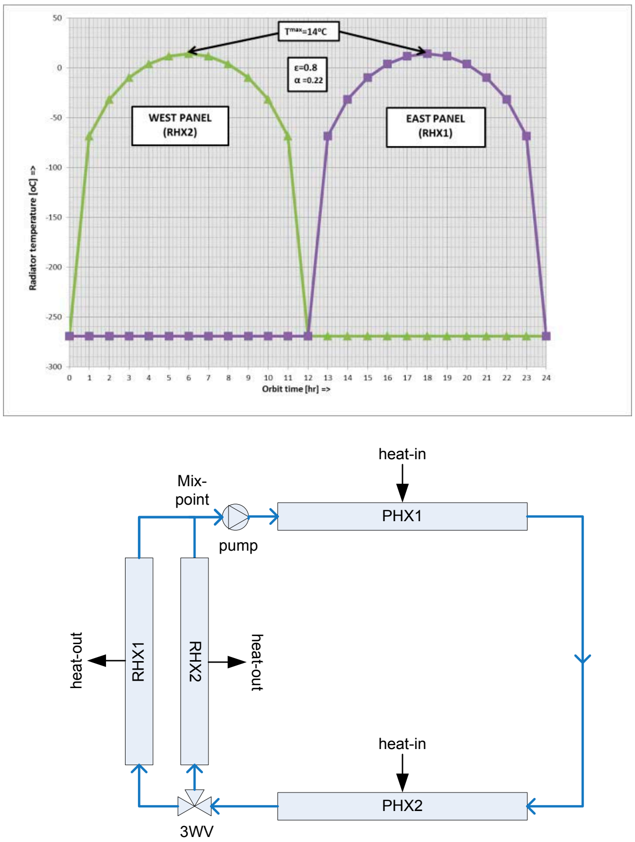

Figure 5 A 24 hour's orbital heat rejection cycle on the East and West panels of a geostationary satellite (left). MPFL with the West panel as second radiator (RHX2) replacing the bypass (right)

A gradual flow change is recommended to prevent that cold fluid from the radiator panel directly enters the pump inlet. For improved temperature stability a second valve could be implemented to regulate the flow through each radiator panel individually. This, however, increases the number of loop components at the cost of reduced system reliability. As analysis showed that although the heat rejection capability of the panel is significantly reduced under 90^o solar for a circulating fluid above 14^{o}C some cooling is still available. In fact this residual cooling eliminates the need for a valve making a valve-less MPFL possible. See Figure 6 for the proposed valve-less arrangement by serial placement of the radiator panels and payload sections. Alternatively for improved orbital temperature stability the payload sections could be cross-linked e.g. by parallel tubing or by the payload structure.

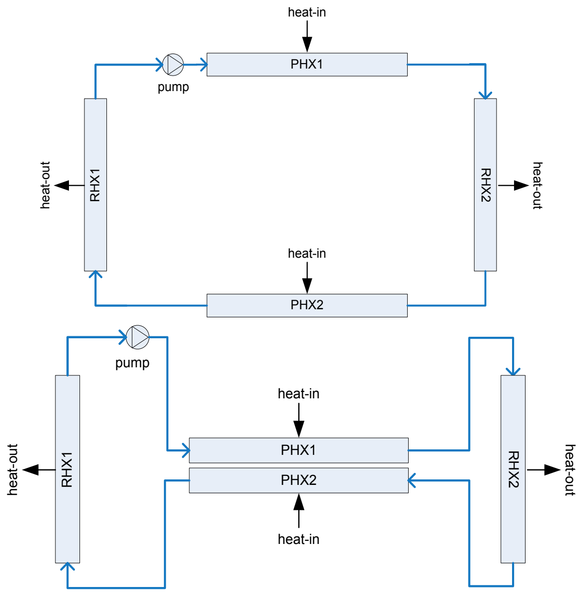

Figure 6 Valve-less MPFL with serial payload and radiator sections (left) with cross-linked PHX for improved stability (right)

For the valve-less MPFL limited controls are available (1) pump speed (2) pump on/off and (3) heater power. Without the valve the average loop temperature goes up and down with the total load, however, the serial arrangement largely compensates for solar and load variations automatically. Is this sufficient to ensure orbital temperature stability? The valve-less MPFL should be switched off below a threshold temperature when additional cooling is not needed. A preliminary orbital temperature stability analysis using a thermal model of the valve-less MPFL is discussed in the next paragraph.

III. Thermal Analysis

For an investigation of the orbital temperature stability of the valve-less MPFL a preliminary design was defined for a typical geostationary satellite (dimension ca 2x2x4m) with a 35 meters loop, based on existing MPFL components. The working point is selected at the lower RPM to reduce the power consumption of the RT pump.

E. Design assumptions valve-less MPFL for a typical geostationary satellite

- MPFL is secondary loop system (e.g. loop failure is not critical)
- East and West panels — $A=2x1.5m^2$, $\alpha=0.2$, $\varepsilon=0.8$
- Pump-in temperature — 20-50^{o}C (used for 'top' cooling)
- Load cases — 0-1000W @ ΔT=0-15^{o}C
- Tubing length — 35m (PHX:2x2m,RHX: 2x8m, transport lines: 15m, 40 x 180^o turns)
- Tube ID — 6 mm
- Loop Volume — 1.4 litre
- Fluid — Galden HT80®
- Accumulator size — 0.35 litre (redesign required)
- Fluid Mass — 2.4 kg
- Nominal working point RT pump at 18.000 RPM (34% efficiency, ca 23 W power consumption)
  - Δp= 2.4-2.7 bar, Φ_m= 205 kg/hr (115 l/h)
- 'Satellite' assumptions (for transient analysis)
  - Payload mass — 2x100 kg (aluminium)
  - Radiator mass — 2x50 kg (aluminium)
  - PHX crosslink — 50W/K (parallel tubing)

- Thermal Resistance Fluid to Tubing per meter
    - C_{PHX} = 17-33 W/K , C_{RHX} = 17-33 W/K

F. MPFL Thermal model

As starting point of the analysis a thermal/hydraulic model (using ThermXL®) of the above valve-less MPFL is constructed with nearly 60 nodes representing the payload and radiator tubing. The tubing is connected to a representative 'satellite model' with assumed loads and thermal masses for transient calculations. Surely these satellite parameters shall be fine-tuned for realistic applications. The MPFL model includes fluidics nodes for the calculation of the hydraulic resistances, pressure drops, temperature gradients and the accumulator size based on the physical properties of Galden HT80® such as density, heat capacity, viscosity, and expansion as function of temperature. For the calculation of the hydraulic resistance the full loop length of 35 meter is used including 40 x180^o bends. Since for the RT pump performance curves for Galden HT80 were not available at the time of the analysis, the field-map of a hydraulically similar fluid Galden Zt85 was used for performance analysis which is considered within 20% accurate. The assumed size for the radiator panels is A=1.5 m^2 (with α=0.2 , ε=0.8), chosen to achieve a maximum pump-in temperature of about +45^{o}C for a 1000W load and 1400 W/m^2 solar radiation on the RHX1.

G. Steady State calculation

The following steady state cases (Table 1) have been analysed with the thermal/hydraulic model for assumed payload powers of between 500W to 1000W and Q_{solar} between 700 W/m^2 to 1400 W/m^2 to estimate the loop temperature extremes. Case V, with zero solar on both radiators, represents the orbital 'turning point' i.e. the coldest orbital temperature of the system. The steady state analysis is *worst case* indicating maximum temperature gradients obtained under fixed load conditions and continues fluid flow, neglecting orbital variations and satellite thermal masses that damps the extremes. For most of the analysis the working point of the pump was kept constant at 205 kg/hr but in practice varies a little related to hydraulic resistance variations due to fluid temperatures in the loop.

Case	Flow rate [kg/hr]	PHX1 [W]	PHX2 [W]	RHX1 [W/m^2]	RHX2 [W/m^2]	Total load [W]
SS-I	205	500	500	1400	0	1420
SS-II	400	500	500	1400	0	1420
SS-III	205	500	500	0	1400	1000
SS-IV	205	500	500	0	700	1000
SS-V	205	500	500	0	0	1000
SS-VI	205	0	500	1400	0	920
SS-VII	205	0	500	700	0	710
SS-VIII	205	0	500	0	0	500

Table 1 Steady state analysis cases for the valve-less MPFL

Steady state results

The steady state results (Table 2) are *worst case* indicating the loop temperatures and gradients under the assumed conditions and continues operation of the pump, neglecting orbital variations and satellite thermal masses.

Case	Pump-in [^{o}C]	ΔT_{PHX1} [^{o}C]	ΔT_{PHX2} [^{o}C]	ΔT_{RHX1} [^{o}C]	ΔT_{RHX2} [^{o}C]
SS-I	47.8	8.2	8.4	-5.2	-11.8
SS-II	46.6	4.1	4.2	-2.6	-5.6
SS-III	44.6	8.3	8.3	-12.8	-5.1
SS-IV	33.2	8.5	8.6	-10.6	-7.1
SS-V	20.4	8.8	9.0	-9.2	-9.2
SS-VI	19.0	0.0	9.3	-1.4	-8.3
SS-VII	1.8	0.0	9.8	-3.4	-6.9
SS-VIII	-19.6	0.0	10.4	-5.8	-5.3

Table 2 Steady state analysis results for the valve-less MPFL

The steady state analysis shows that the response of the serial loop is robust for change in load cases:

- **Case VI**: The radiator temperature gradient does not go to zero with maximum solar radiation indicating residual heat rejection to space.
- Case **I<->II**: When the pump speed increase from 205 to 400 kg/hr this hardly affects the Pump–in temperature but only the thermal gradients.
- **Case I<->V:** The temperature variation between the hottest and coldest point in the orbit is ±13.7°C
- **Case I<->III**: Switching maximum solar heat input from the East to the West panel shows a small Pump-in temperature variance of ±1.5°C
- **Case III<->IV**: A solar input reduction from 1400W/m^2 to 700W/m^2 shows an Pump-in temperature reduction of -11.4°C (=0.015K/W)
- **Case I <-> VI**: A load reduction from 1000W to 500W shows an additional Pump-in temperature reduction of -27.4°C (=0.05K/W)

A transient analysis is performed to investigate orbital temperature stability.

H. Orbital transient analyses

For the transient analysis with the valve-less thermal model a 2x700W/m2 solar heat flux on both radiators panels is used as start point of an orbital 'average' temperature. The nominal mass flow is assumed 205 Kg/hr. The load on the PHX1 and PHX2 is assumed to be 500W. After 72 hours (i.e. 3 simulated orbits for stabilisation) the PHX1 load is halved to 250W to investigate the temperature response of the system. The radiator mass (aluminium) has been assumed 50 kg and the payload mass (aluminium) 200-400 Kg. To verify the orbital temperature stability for pump speed variations the mass flow was varied between 102-307 kg/hr. A 'thermal cross link' of 0-50W/K between the two payload sections was assumed for damping the payload temperature extremes, simulating disconnected or closely connected tubing. The following transient cases have been analysed in Table 3.

	Flow rate	Payload Cross-link	PHX mass	RHX mass	Max ΔT in PHX	PHX temperature stability after 3 orbits
Case	[kg/hr]	[W/K]	[kg]	[kg]	[°C]	[°C]
TR-I	205	-	2x200	2x50	±8	±1.5
TR-II	205	-	2x100	2x50	±8	±3
TR-III	205	50	2x100	2x50	±8	±1
TR-IV	102	50	2x100	2x50	±15	±1.5
TR-V	307	50	2x100	2x50	±5	±1

Table 3 Transient analysis cases for the valve-less MPFL

With the tubing length of 35m and a nominal fluid velocity of about 1 m/s the fluid circulation time is ca 35 sec. An important parameter for the transient calculation is the choice for the time step which should not be confused with the time step which is related to the thermal response time. After trying time steps of 10, 30, 60, 120, 300 and 600 seconds a time step of 120 sec gives an optimal results for a reasonable calculation time. A shorter time step results in long calculation times and a longer time step results in numerical instabilities in the calculations.

Transient analysis results

Transient analysis (Figure 7) shows the orbital temperature stability of the two payload sections (is estimated in the range of ±3°C for a constant load of 1000W for case TR-II. The graph show downwards trend because after three orbits for stabilisation the payload power is reduced to 750W. This can be improved down to ±1°C by crosslinking the payload sections (Figure 6) and/or at an increased mass of the payload. Loads variations can also be compensated using heaters on the payload to damp temperature fluctuations.

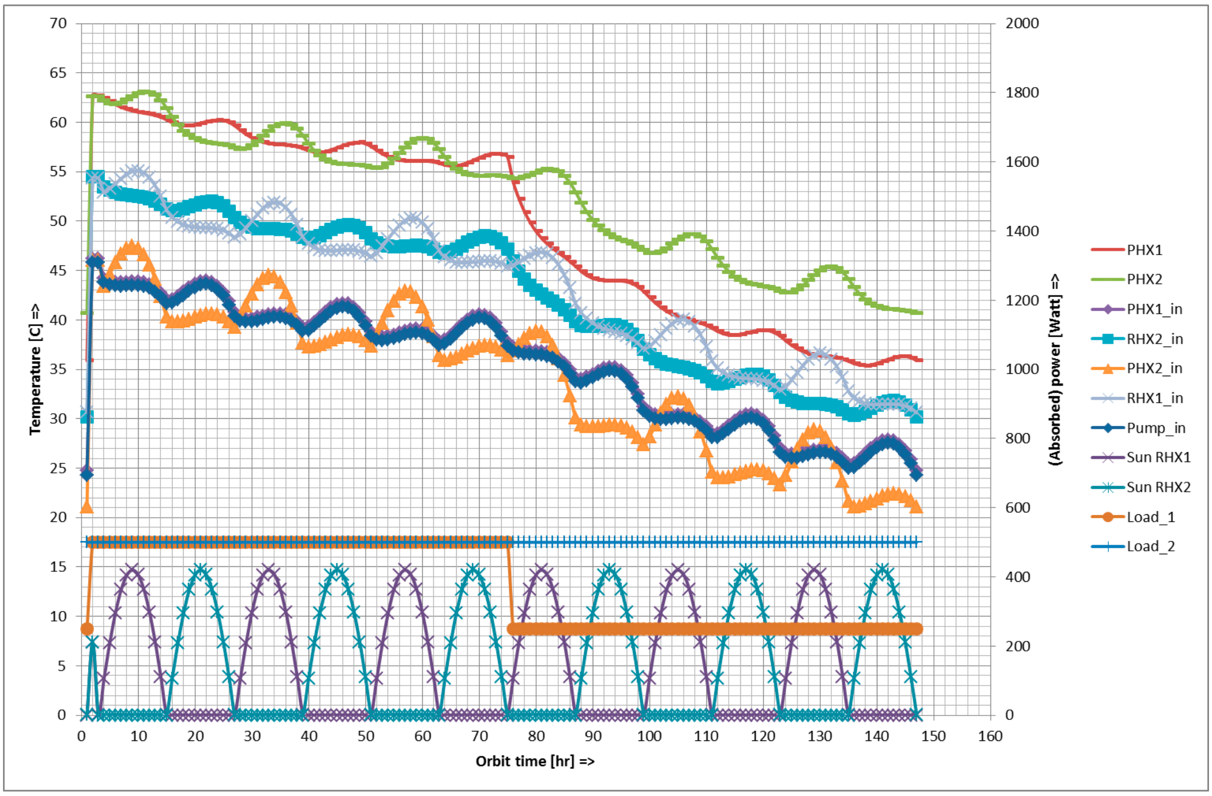

Figure 7 Orbital transient analysis valve-less MPFL without payload cross-link (TR-II). After three orbits the payload power is reduced from 1000W to 750W

To summarize the transient orbital analysis:

- The temperature gradients across the PHX/RHX sections are between 0-15°C for load cases between 0-500W at a constant pump speed of 200kg/hr.
- Transient analysis revealed a ±1-3°C orbital temperature stability (at constant load) that can be improved at higher payload and radiator masses and cross-linking the payload sections.
- Varying the pump speed hardly influences neither the temperature stability nor the temperature level of the loop.

In case small orbital temperature variations are allowed for the payload equipment (or compensate with heaters) the valve-less MPFL is well suited to provide for 'top' cooling for a geostationary satellite to extend life time and increase system reliability. This can be achieved with existing 3kW MPFL hardware with a smaller accumulator.

Transient orbital analysis of the valve-less MPFL in a satellite TMM is recommended for design of the average temperature level and verification of the thermal stability of the payload.

IV. Breadboard Testing

The existing full scale test-setup of the 3kW MPFL (Figure 4) could be relatively easily modified to verify the orbital stability of the valve-less MPFL. However, the breadboard setup is not fully comparable with thermal model prediction as discussed in section III because the tubing is longer, the load higher and the pump speeds and flows are adjusted to higher RPMs. The 3kW MPFL test-setup was modified (Figure 7) to interconnect a second Radiator Heat Exchanger (RHX2) and the PHX was split in two parts PHX1 and PHX2 of 35m each. The Bypass Valve Assembly (BPA) was disconnected. Since the total hydraulic resistance was only slightly increased the working point for the RT pump was nearly similar compared to the original set-up with the BPA connected to a single radiator.

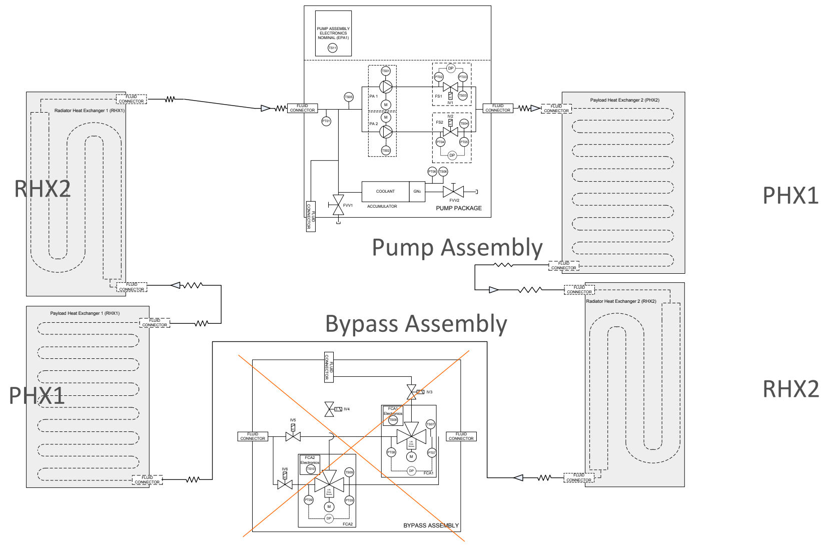

Figure 7 Schematic of the modified MPFL test-setup bypassing the valve assembly to obtain a valve less loop

The two payload sections PHX1 & PHX2 were powered with increasing loads, next to that, the cooling of RHX's were switch on and off to simulate a worst-case orbital variations in the case that one of the radiators is irradiated by the sun losing its heat rejection capability. Since the set-up has a low heat capacity (mainly tubing and components) the thermal response is fast i.e. worst case compared to slow orbital variations and high payload and radiator masses. The worst case thermal stability of the valve-less design is verified under varying pump speeds, increasing loads and loop temperatures and active radiator surfaces. The thermal gradients across both payload sections (PHX1, PHX2) and radiator sections (RHX1, RHX2) and the temperatures at the in and outlets of each section are measured. For the system test the loop temperature is controlled by the set-point of the chillers. In a space environment the radiator temperature varies its heat rejection with T^4. This has been simulated during the test by increasing the chiller temperature with the load. To limit the total test duration the radiator switching 'per half orbit' is shortened from 12 hours to ca 20-30 minutes which is sufficient to achieve a stationary flow and stable thermal conditions.

To summarize the valve-less test setup:

- Chiller temperature was set between 20-50°C.
- The pump speed was varied between:
  - 215 kg/hr @ 15000 RPM (Δp = 2.3 bar)
  - 284 kg/hr @ 20000 RPM (Δp = 3.7 bar)
  - 360 kg/hr @ 26000 RPM (Δp = 5.8 bar)
- Increasing loads on PHX1&2 of:
  - P=500W (250 W per payload section)
  - P=1000W (500 W per payload section)
  - P=2000W (1000 W per payload section)
- To simulate orbital conditions: RHX1 & RHX2 cooling was switched between:
  - ON (1= active cooling viewing deep space)
  - OFF (0 = no cooling, irradiated by the sun).

Breadboard Temperature gradients

In total 40 test cases have been executed. In Table 4 a few test cases are highlighted for varying pump speeds. For this test the loop runs at about 50°C and both the radiator chillers are ON. A load of about 1000W is applied to both PHX1&2 (2000W total). The pump speed is varied between 15.000-26.000 RPM. The corresponding mass flows and temperature gradients across the payload sections PHX1&2 and the radiator sections RHX1&2 are measured after 20-30 minutes to achieve stationary conditions.

Flow	Pump Speed	dP_pump	dTphx1	dTphx2	dTrhx1	dTrhx2
kg/h	RPM	bar	°C	°C	°C	°C
286	20000	3.75	11	11	-10	-11.2
366	26000	5.81	8.8	8.8	-7.9	-9.3
215	15000	2.27	14.5	14.5	-13	-14.3

Table 4 Pump speed variations at 50^{o}C (@ 2000W load)

This pump speed variation test was repeated at several loop temperatures and load conditions resulting in the thermal gradients plotted as potted in Figure 8. The thermal gradients increase up to with load (or cooling power) and reduce with increasing pump speed consistent with a heat capacity of Galden HT80® of about 1000 J/kg/K.

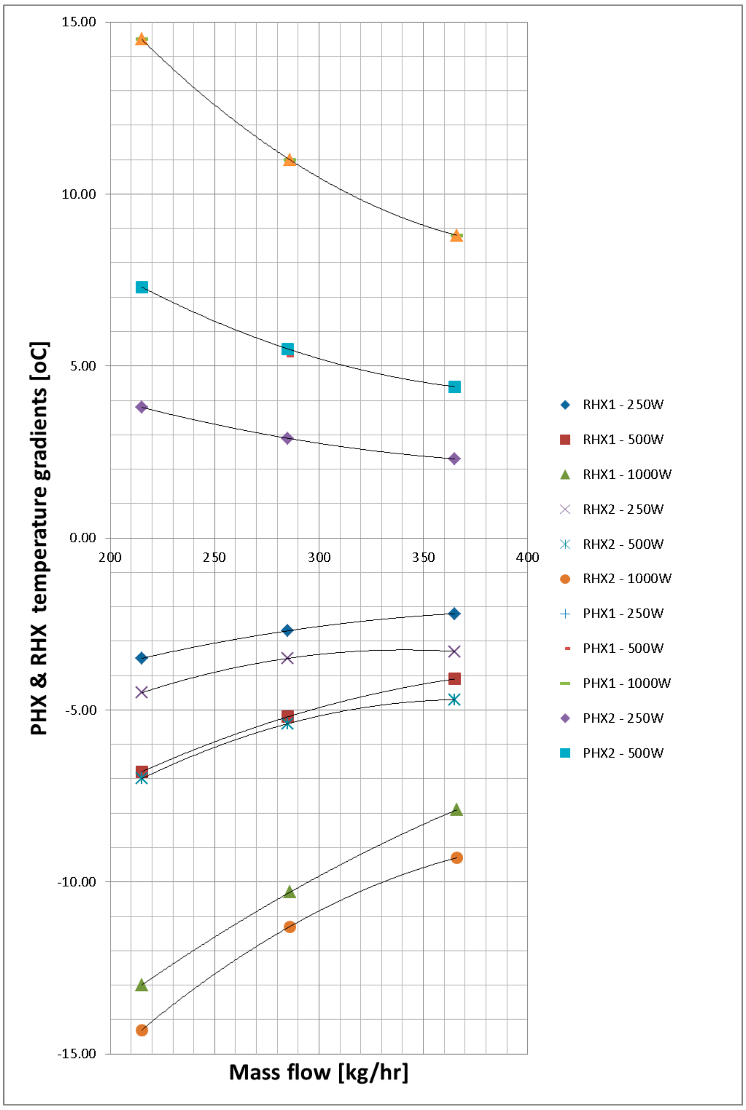

Figure 8 Mass flow versus temperature gradients under load conditions between 250-1000W for the valve-less MPFL breadboard test

Simulated orbital temperature stability

See Table 5 for an example of a simulated orbital test by switching between the radiators under varying load conditions. For this test the loop runs at about 50°C and the RHX chillers are switched ON or OFF simulating orbital cooling variations. A partial or full load of about 500 or 1000W is applied to one or both PHX1&2 (1500W total). Pump speed is fixed at 20.000 RPM with a mass flow of 286 kg/h. The corresponding temperature gradients across the payload sections PHX1&2 and the radiator sections RHX1&2 are measured after 20-30 minutes to achieve stationary conditions.

P_{PHX1}	P_{PHX2}	RHX1	RHX2	$T_{Pump\text{-}in}$	ΔTphx2	ΔTphx2	ΔTrhx1	ΔTrhx2
W	W	ON/OFF	ON/OFF	°C	°C	°C	°C	°C
1003	1003	1	0	53.6	10.2	11.4	-18.3	-2
499	1003	1	0	52.2	5.2	11.3	-14.2	-1.3
499	1003	0	1	*55.7*	6	11.1	-0.8	-15
499	1003	1	0	51.6	5	11.3	-13.5	-1.8
499	1003	0	1	55.3	5.9	11.1	-15.2	-0.6
1003	498	0	1	59.0	11.1	5.6	-1.4	-13.7
1003	498	1	0	52.1	10.4	6.1	-14.4	-1.1
1003	498	0	1	59.2	10.9	5.6	-13.6	-1.3
1003	498	1	0	52.1	10.4	6.1	-14.3	-1

Table 5 Measured 'orbital' temperatures at 50°C under varying cooling and loads conditions (@1500W, $\dot{m}$ =286 kg/hr)

Results orbital stability testing

The orbital thermal stability of the valve-less loop was successfully demonstrated by switching between both radiators at several pump speeds under varying load case. The measured maximum temperature variation is ±5.5°C (@ 2000W load) at any point in the loop. Since the test set-up hardly has heat capacity and the payload are not cross-linked it is expected that the orbital stability is significantly better related to the thermal mass of the payloads and radiator, which should be confirmed by extended thermal analysis. Crosslinking payload sections could improve the orbital stability.

V. Conclusion

A valve-less MPFL for 'top' cooling for geostationary satellites can be achieve with existing MPFL components. Only a modified 0.35 litre accumulator is required. The valve-less MPFL could be a preferred solution because it reduces the number of components and increases the system reliability. The tested *worst case* orbital temperature variation is ±5.5°C (@ 2000W load) at any point of the loop but this shall be verified with orbital thermal analysis including satellite thermal masses and load variations.

For the valve-less MPFL the following design guidelines shall be considered to ensure the thermal stability of the system in orbit.

1. Establish the working point for the pump (i.e. pressure head versus flow rate) and accumulator sizing (i.e. loop volume) is related to the required mass flow for the allowed temperature gradient and corresponding tube diameter and length.
2. Establish maximum load and highest allowed payload design temperature for the sizing of the E/W radiators. Take into account the thermal gradients between the payload and the radiators based on the mass flow rate. One radiator panel must be sufficient to reject the maximum load to deep-space.
3. Establish the minimum load and lowest payload temperature. Implementation of survival heaters for zero loads, failure cases (proposed pump switch-off at 20°C) and commissioning could be considered.
4. Heater control could be considered to improve temperature the payload stabilization.

5. Establish load (variances) and allowed gradients/temperature fluctuations to set the mass flow rate based on the fluids heat capacity and corresponding pump speed. The pump speed can be reduced for lower loads or to allow lager temperature gradients.
6. The pump can be either operating at several speeds or switched off below a threshold temperature of 20^{o}C. The thermal stability improves with increasing pump speed.
7. Transient orbital analysis is required for verification of the thermal stability of the integrated loop system.

Acknowledgments

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Computer Software

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