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NLR-TP-2018-232 | June 2018

Development of a Passive Bypass Valve for one and two Phase Fluid Loops for Space Applications

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EXECUTIVE SUMMARY

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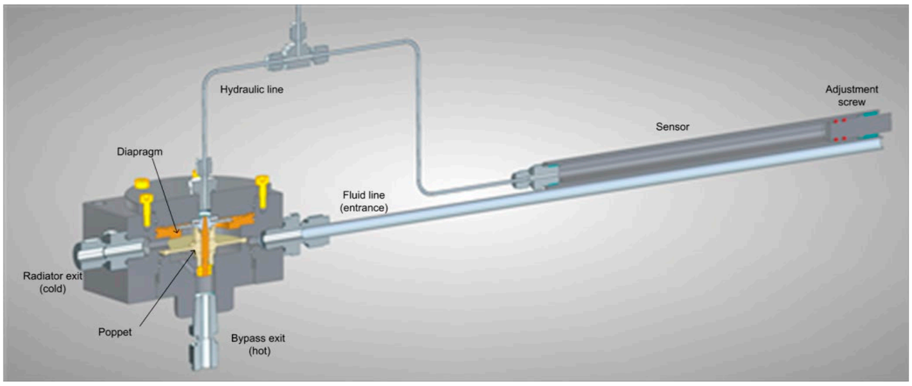
Development of a Passive Bypass Valve for one and two Phase Fluid Loops for Space Applications



Engineering Model of the Passive Bypass Valve. The flow distributor (light yellow poppet) is hydraulically actuated via the capillary tube (hydraulic line) connected to a sensor filled with a non-compressible fluid.

Problem area

The cooling demands for satellites are steadily increasing as are the heat flux rate of payloads. To cope with these demands, single-phase and two-phase fluidic cooling loops are being developed by European Satellite primes for integration in the next generation satellites. To improve the performance of these loops, innovative components are currently being developed. One of these components is the Passive Bypass Valve (PBV) which autonomously diverts flow from the radiator when thermal dissipation is low, enabling the concerning equipment to be maintained within the operating temperature range.

Description of work

The objective of the project was to develop an Engineering Model (EM) of the PBV for single-phase and two-phase Mechanically Pumped fluid Loops (MPL) and Loop Heat Pipes (LHP) up to TRL5. The development team consisted of Netherlands Aerospace Centre (NLR) as prime contractor and OHB Sweden (OHB-SE) and Moog Cheltenham (Moog-UK) as subcontractors.

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KNOWLEDGE AREA(S)
Space Applications

DESCRIPTOR(S)
Valve
Fluid Loop
Bypass
Space

Results and conclusions

A literature study patent survey (indicating no problems related to IPR) to prepare for the trade-off study was done for several variations of conceptual designs of the bypass valve including:

- Type 1: Bi metallic actuated
- Type 2: Differential temperature actuated
- Type 3: Wax actuated
- Type 4: Thermostatic sensor actuated.

Technical and non-technical requirements as well as system aspects were rated as well as breadboard testing was done for the most promising concepts. The valve type 4 was selected for the design and manufacturing of the Engineering Model (EM1) Passive Bypass valve.

The EM valve (*see figure*) is hydraulically actuated via capillary tube by expansion of a liquid (as function of temperature) inside a remotely located sensor.

Related to significant design modifications required for the EM1, the environment tests were postponed to the QM, to achieve a focus on redesign (EM2) and performance testing. The modified EM2 valve showed an adjustable range (±9^{o}C) and repeatable switching as function of temperature (±10^{o} C) in three orientations tested in the single phase MPL. A small hysteresis of ±1.5^{o}C (up or down in temperature) has been observed which could be related to the thermal inertia of the hydraulic liquid.

The two-phase LHP test showed that the valve stabilized the sensor (payload) temperature around 33^{o}±5^{o}C (upper limit of the valve) at a condenser temperature of -20^{o}C under varying load cases ranging from 500W down to 20W.
The conclusion was that EM2 valve has been successfully developed and performance tested to TRL 4-5. Activities were defined to improve its maturity further to TRL 5-6.

Applicability

One and two phases cooling systems (MPL and LHP) for space applications.

GENERAL NOTE

This report is based on a paper presented at the International Conference for Environmental System (ICES), July 8-12, 2018, Albuquerque, New Mexico, USA

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Development of a Passive Bypass Valve for one and two Phase Fluid Loops for Space Applications

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To cope with increasing cooling demands, single-phase and two-phase fluidic cooling loops are being developed by European Satellite primes. Innovative components are currently being developed such as recently the Passive Bypass Valve (PBV) which development is described in this paper. The PBV autonomously diverts flow from the radiator when thermal dissipation is low, maintaining the equipment within the operating temperature range. The objective the project initiated by the European Space Agency (ESA) was to develop an Engineering Model (EM) of the PBV for single-phase and two-phase Fluid Loops up to TRL 5. The development has been conducted by the Netherlands Aerospace Centre (NLR), NAMMO-United Kingdom and OHB-Sweden. A trade-off study was done for conceptual designs of the bypass valve including: (1) Bi metallic actuated, (2) Differential temperature actuated, (3) Wax actuated (4) Thermostatic sensor actuated. Technical as well as system aspects were rated and weighted as well as breadboard testing was done for the most promising concepts. The thermostatic valve type 4 was selected for the design and manufacturing of the Engineering Model (EM). The EM valve is hydraulically actuated via a capillary tube by expansion of a liquid Galden HT80 inside a remotely located sensor. The EM valve showed an adjustable range (±9^{0}C) and repeatable switching as function of temperature (±10^{0}C) in three orientations tested in the single phase Mechanically Pumped Loop (MPL). A small hysteresis of ±1.5^{0}C (when going up or down in temperature) has been observed which could be related to the thermal inertia of the hydraulic liquid. The two-phase Loop Heat Pipe (LHP) test showed that the valve stabilized the sensor (payload) temperature around 33^{0}±5^{0}C (upper limit of the valve) at a condenser temperature of -20^{0}C under varying load cases ranging from 500W down to 20W. The conclusion was that EM valve has been successfully developed and tested to TRL 4-5. Activities are defined to improve its maturity further to TRL 6.

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Abbreviations

COP	Cross-Over-Point (i.e. a 50/50 flow distribution between both exit ports)
EM	Engineering Model
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
IPR	Intellectual Property Rights
LHP	Loop Heat Pipe
MPL	Mechanically Pumped Loop
MSL	Mars Science Laboratory
NAMMO	Nordic Ammunition Company
NLR	Netherlands Aerospace Centre
OHB	Orbitale Hochtechnologie Bremen
PBV	Passive Bypass Valve
QM	Qualification Model
TRL	Technology Readiness Level

I. Introduction

The cooling demands for satellites are steadily increasing as are the heat flux rate of payloads. To cope with these demands, single-phase and two-phase fluidic cooling loops are being developed by European Satellite primes for integration in the next generation satellites[1,2,3,6,7,8]. To improve the performance of these loops, innovative components are currently being developed. One of these components is the Passive Bypass Valve (PBV) which autonomously diverts a liquid or vapour flow from the radiator in case the thermal dissipation is low, enabling the equipment to be maintained within their operating temperature range. The development of the Engineering Model (EM) of the Passive Bypass Valve up to TLR 4-5 is described in the paper highlighting the developments steps taken in the period between 2014 and 2017. The team consisted of Netherlands Aerospace Centre (NLR) as prime contractor and OHB Sweden (OHB-SE) and Nammo Cheltenham (Nammo-UK) as subcontractors. The main requirements for the development of the Passive Bypass Valve are listed in Table 1.

From the start an extensive literature study and patent assessment was done indicating no problems related to IPR since all relevant industrial patents were expired. Thereafter a trade-off study was conducted for several conceptual variations of the valve design including: (1) Bi metallic, actuated, (2) Differential temperature actuated, (3) Wax actuated (4), Thermostatic sensor actuated. Technical requirements and system design aspects were rated and weighted as well as breadboard tests were done on the most promising concepts. Eventually valve type 4 (based on a commercial thermostatic valve) was selected for the design of the Engineering Model (EM) valve. The EM is hydraulically actuated via capillary tube by expansion of a liquid (as function of temperature) inside a remotely located sensor. The EM has been successfully performance tested in two systems: a single phase Mechanically Pumped Loop (MPL) system and a two-phase Loop Heat Pipe (LHP) system.

Table 1 Main requirements for the Passive Bypass Valve

Requirement	Remark	Target	PBV EM Achieved	Unit
Flow Range	Valid for liquid and vapour	2	2	litre/minute
Internal Pressure	Suitable for Ammonia	65	45	bar
Flow Distribution	port 1 <-> port 2	0%-100%-0%	0%-100%-0%	
Temperature Range	By adjustment	20	19	ºC
Switch range	By design	±5	±10	ºC

II. Applications of the bypass valve

A typical application of the passive bypass valve is schematically shown in Figure 1 for a single-phase mechanically pumped loop (MPL) as being used for example for the Martian Rover [4,5] (Figure 2) or as proposed for high power communications satellites (Figure 1). Two-phase mechanically pumped loops are similar but, instead of allowing a temperature increase across the payload, the evaporation set-point stabilizes the payload temperature in a narrow band which can be required in some cases. For both the single- and two-phase MPL, the bypass valve operates in the liquid regime.

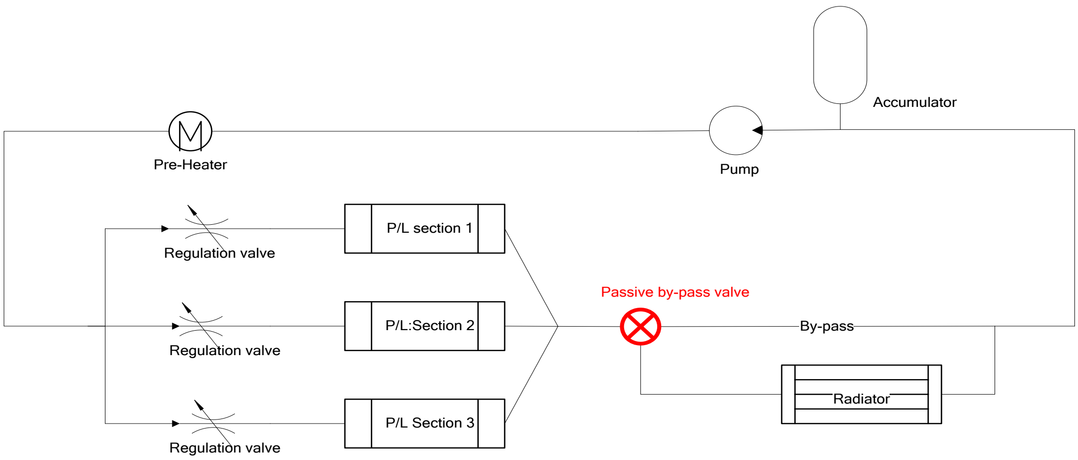
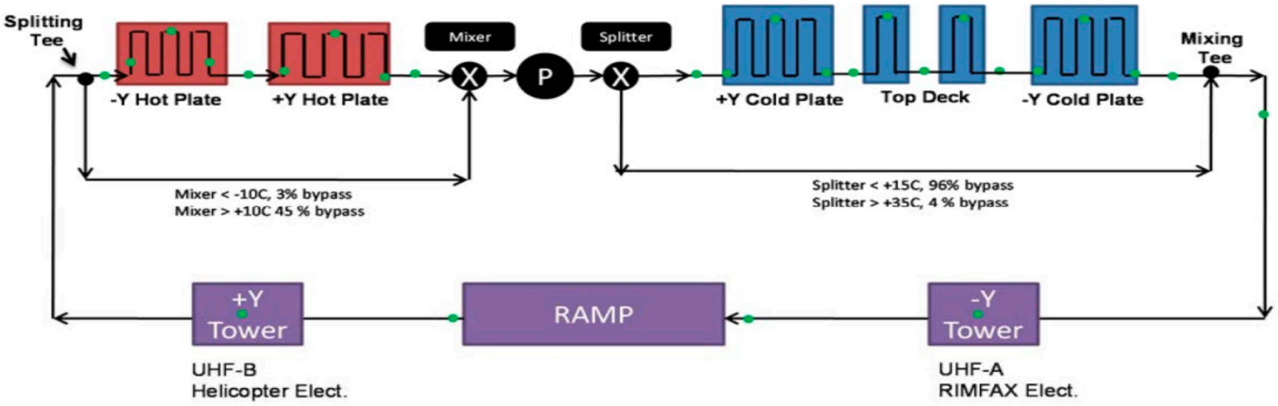


Figure 1 Typical Mechanically Pumped Loop Lay-out (single phase) for large spacecraft



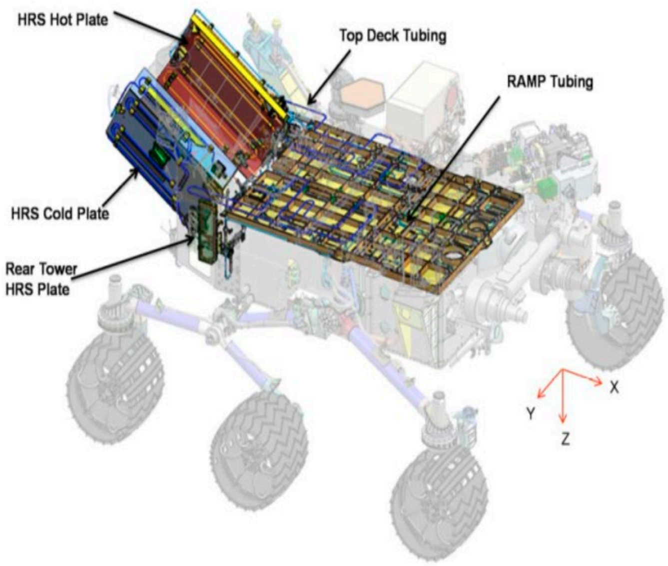


Figure 2 Single Phase Mechanically Pumped Loop Lay-out on the NASA MSL[4,5] The mixer and splitter valves are potential applications of the Passive Bypass Valve for regulation of the liquid through the hot and cold phases respectively

Other foreseen applications besides the single and two phase mechanically pumped loops are for Loop Heat Pipes. The LHP with a bypass valve in the vapour line is schematically shown in Figure 3. Designs have been developed previously which involve electrically actuated valves, temperature sensors and electronic controllers to determine and enable the appropriate path for the working fluid. However, these designs tend to be expensive, heavy and consume power. Also the low load thermal stability is a point of concern. The Bypass Valve avoids these disadvantages by being a self-contained mechanical valve with automatic temperature sensing and flow control, and with no influence from pressure variations. For LHP applications the bypass valve operates in the vapour regime.

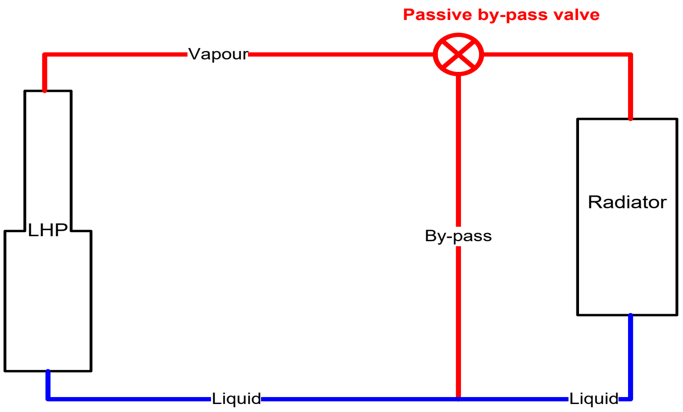


Figure 3 Passive Bypass Valve installed in the vapour line of a Loop Heat Pipe

III. Valve Development Overview

A. Inventory of valve concepts

As part of the technology survey, potential valve and valve actuator technologies identified have been considered for the design trade-off. After a literature study and a patent survey, the trade-off included technologies such as wax actuators, bimetallic strips and (amplified) differential expansion actuators. The various actuators produce a change in geometry proportional to the temperature or a difference in temperature between the actuator and the valve housing. This change in geometry is used to move a valve poppet from one outlet to another, thereby transferring fluid from one port to another, from the radiator to the by-pass, or vice versa.

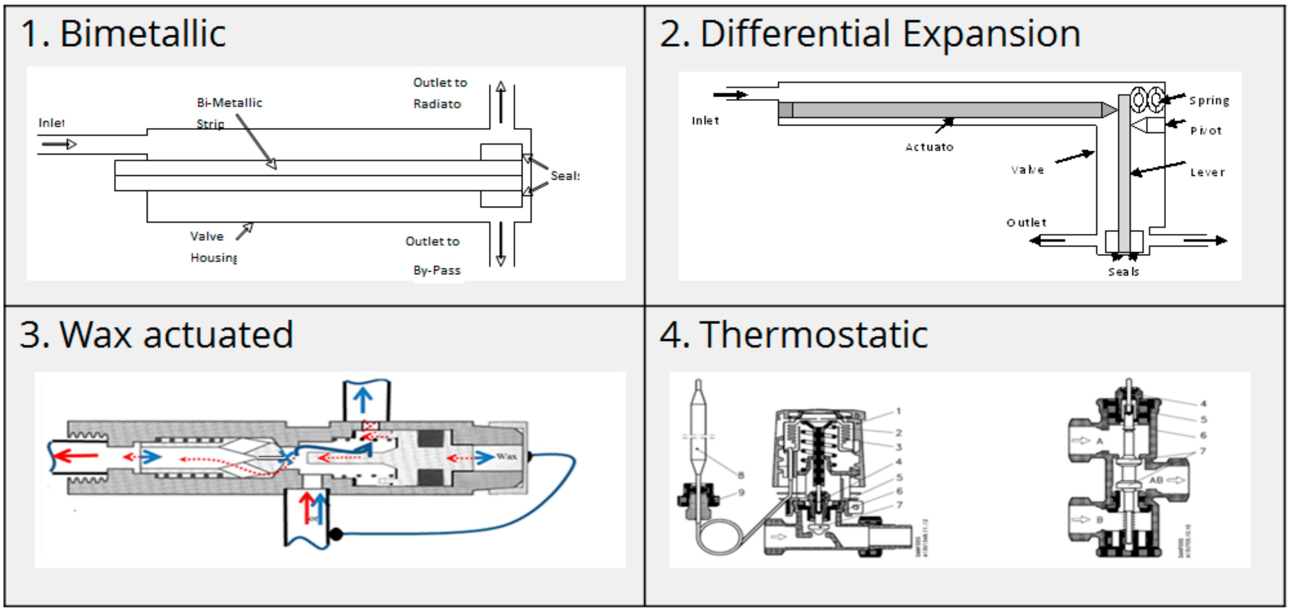


Figure 4 Investigated valve concepts

Four thermostatic valve actuation principles were investigated (Figure 4)

- Type 1 Bimetallic actuated
  Two metal strips attached to each other with a difference in thermal expansion coefficient causes a bending related to the temperature.
- Type 2 Differential expansion actuated
  The valve is constructed of metals with different thermal expansion coefficients causing a displacement with respect to the housing related to the temperature.
- Type 3 Wax actuated
  Melting or solidifying of a wax causes a change in thermal expansion related to the temperature which is transferred to the valve poppet.
- Type 4 Thermostatic sensor actuated
  Thermal expansion of a liquid or vapour as function of temperature is transferred via a capillary tube from the sensing location.

Conceptual design variations for each valve technology type are indicated with a capital letters from A to D. Table 2 lists the technologies and conceptual variations for the valve design which were investigated for the trade-off.

Table 2 Investigated valve concept variations for the trade-off study

Valve Type	**Actuation**	**Design Concept**	**Description**
1	Bimetallic	**A**	Beam fixed at one end (cantilevered)
		B	Beam fixed at both ends
2	Differential Expansion	**A**	Thermal expansion between housing and actuator (lever with pivot point)
		B	Asymmetric tube
3	Wax	**A**	Capsule (squeeze-push)
		B	Flat diaphragm (elastomer)
		C	Corrugated diaphragm (metal)
		D	Bellow (metal)s
4	Thermostatic sensor/reservoir	**A**	2 phase liquid/gas filled
		B	Absorption/gas filled
		C	Liquid filled (industrial)
		D	Liquid filled (household)

B. Breadboard testing

To support the trade-off breadboard tests with promising concepts have been performed. The schematic diagram Figure 6 illustrates the single phase fluid loop breadboard test setup were water is circulated with a pump at a flow of 2l/min and is heated and cooled. The flowmeters 1 & 2 measure the flows through both the valve exit ports. The setup is used to determine the Cross-Over-Point (COP, see Figure 5.) that defines the fluid temperature for which a 50/50 flow distribution is achieved between the exit ports of the valve. Four types of breadboard valve were tested:

- Type 1A: Bimetallic actuated
- Type 2A: Differential expansion actuated
- Type 3D: Wax actuated
- Type 4C: Thermostatic valve (Heimeier)

The first three valve types breadboard valves were constructed with help of Swagelok® components. See Figure 7.

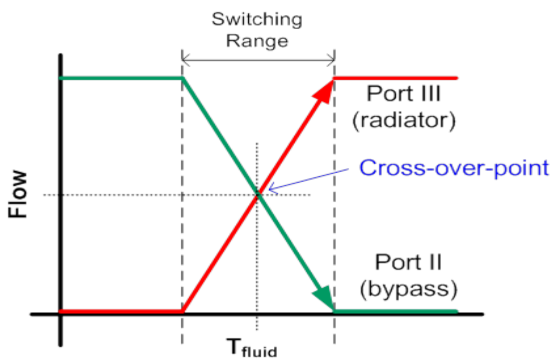


Figure 5 Cross-Over Point (COP)

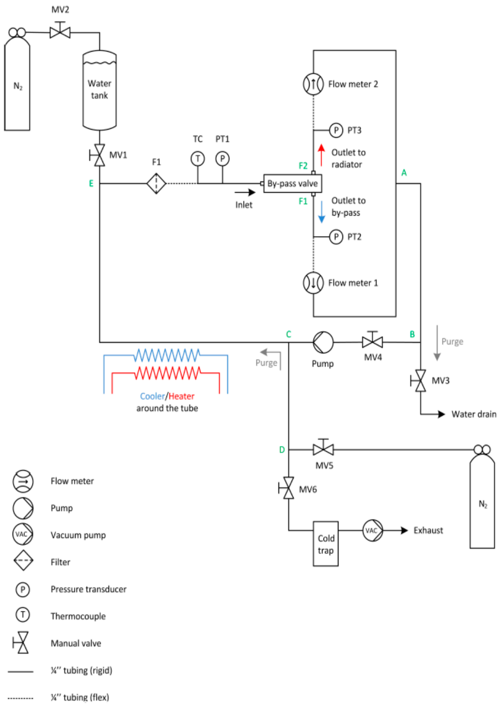


Figure 6 Breadboard test setup used to evaluate the valve performance

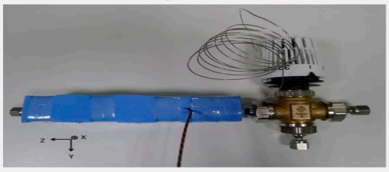
1. Bimetallic (Nammo)	2. Differential Expansion (Nammo)
	
3. Wax actuated (OHB/Nammo)	4. Thermostatic (Heimeier Valve)
	

Figure 7 Tested breadboard valves

The performance of these breadboard valves was largely inconclusive showing hardly any or no switching action. The commercial Heimeier valve (see also Section D) gave an excellent hydraulic performance (Figure 8).The green line indicates a water (inlet) temperature going up and down and the green dotted line is the temperature as measured with a thermocouple on the sensor - which slightly lags behind. Note that this is a functional test comprises a temperature sweep versus flow distribution and that it is not similar as controlling the payload temperature. The blue and red lines indicate the flows through the ports which ‘crossover’ at 1 L/min around a sensor temperature of 30ºC indicated with the red dotted line.

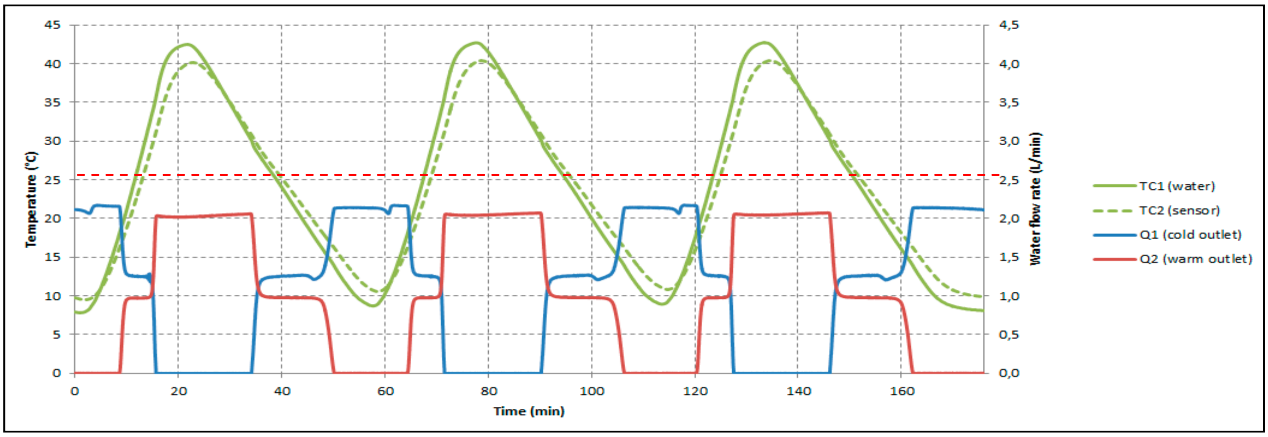


Figure 8 Breadboard test results of the thermostatic valve clearly demonstrating a flow cross-over between the exit ports around 30^{0}C inlet temperature

C. Trade—off study

For a rational comparison of the valve concepts a rating system based on calculations and engineering judgments was used. The following criteria and weighing factors (see Table 3) were used for the comparison of the valve concepts. For each of the criteria a weighting factor was allocated to express their relative importance. The total score for each valve concept is calculated as the sum of the rating [1-10] for all criteria multiplied by the weighting factor [1-5]. It is however outside the scope of this paper to discuss the selection process in more detail. A hydraulically actuated BPV with a liquid filled thermostatic sensor/reservoir (type 4C) was selected and is described in more detail in section D.

Table 3 Trade-off criteria and weighting factors

** 1=not critical; 2= minor; 3= average; 4= important; 5= very important*

Criterion	Description	Weighting factor*
1	Mechanical performance	3
2	Thermal performance	5
3	Hydraulic performance	4
4	System Design Aspects	3
5	Design maturity/space heritage	3
6	Fluid Compatibility	4
7	Patent Infringements	2
8	Ease of manufacturing	2
9	Commercial Price Indication	2
10	Breadboard test results	4

D. Concept selection

An example of an industrial thermostatic design 4C is the Heimeier valve (Figure 9) which was introduced for the breadboard testing for comparison. The Heimeier valve is widely used for industrial and household heating applications and no infringements of patents are to be expected any more. The Heimeier valve has been selected for the breadboard test because the thermal and hydraulic specifications are close to ESAs requirements. However, significant design modifications are to be expected to make it compatible for Ammonia, to extend its life time and to adapt it for space environments. The valve has a sensor metallic bulb (lower right side) containing a hydraulic fluid which is connected to the flow distributor/valve body via a capillary tube. The tube is connected to a bellows which moves a pin up and down depending on the thermal expansion of the fluid. The valve has a plastic knob to regulate the switch-point temperature. The flow distributor (lower left side) has three ports. Fluid enters via Port I and is distributed by the double poppet toward Port II and Port III. Advantages of these valves are the flexible location of the control point (however limited by the capillary length) and the various ways of adapting the switch point and temperature range. Drawback is the use of bellows which can cause lifetime and fatigue issues. A diagram was implemented for the EM PBV to the improve lifetime for space applications. The design of the EM valve is descripted in more detail in section E.

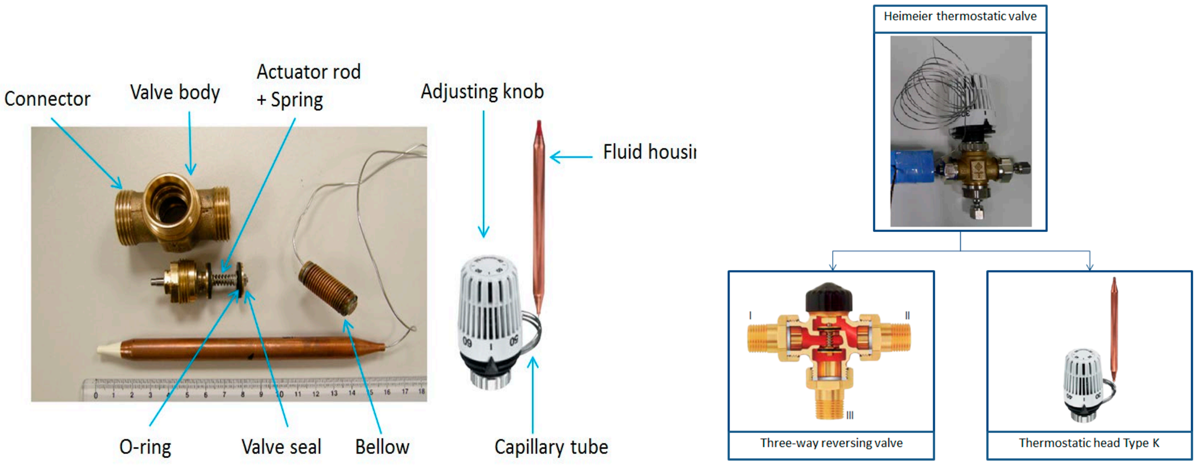


Figure 9 Commercial (Heimeier) thermostatic Valve (4C) as used as reference case for the breadboard testing.

E. EM PBV design

The EM PBV design operates as follows. See Figure 10. The actuator fluid is contained in a sealed volume above the diaphragm hydraulically connected with a capillary tube to a sensor volume. As the sensor is in contact with the environment (or tube) the liquid volume of the actuator will change under temperature moving the diaphragm, pin and the poppet up and down. The poppet distributes the flow between the two outlet ports. As such the temperature of the sensor is directly related to the flow distribution. At high temperatures, the poppet is at its lowest position and the cold outlet (bypass) is fully blocked. A at lower temperatures the poppet is in its highest position and the hot outlet (radiator) is fully blocked. For the hydraulic actuation fluid, Galden HT80 has been selected which has high thermal expansion coefficient of ca 1.2E-3K^{-1} (Figure 12a) and an excellent radiative hardness. HT80 was selected previously during an ESA study (MPFL)[3] for the use in single phase pumped cooling systems in space.

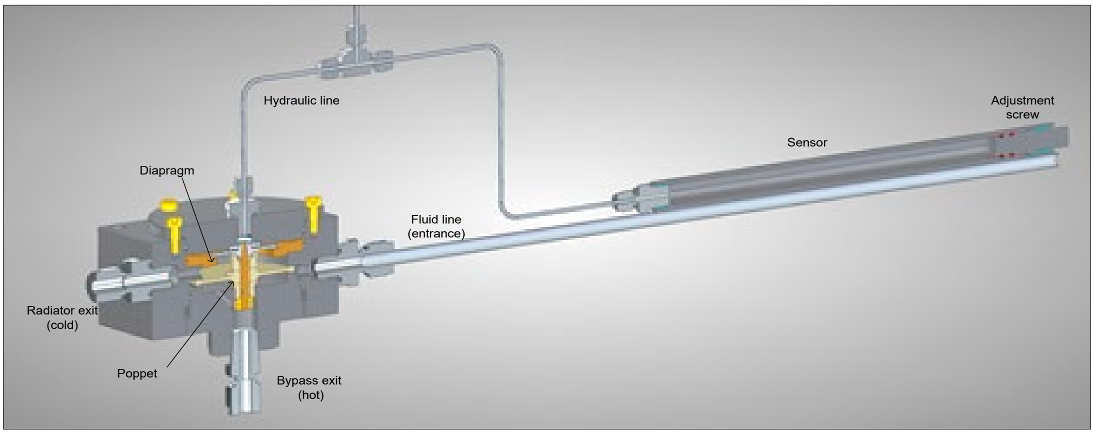


Figure 10 PBV initial design. Diaphragm, with the hydraulic fluid at one side, is connected to single poppet to distribute the flow between the two exit ports. The hydraulic actuator (sensor bulb) is connected (in this example) down the inlet line (tube at the right). The internals are adapted for the improved design.

The EM design is based on a 0.25mm stroke of the pin, a 47mm diameter diaphragm that will deflect by -1mm / +2mm (Figure 12b) before it respectively reaches the cold and hot mechanical stops. The sensing liquid volume and the diaphragm are sized so that the valve will completely open or close over a 10°C temperature range, nominally between +20°C and +30°C.The switch cross over-point (50/50 flow distribution between port 1 and 2) can be tuned by a mechanical adjustment screw altering the sensor bulb volume so change the temperature range of the flow outlets between +10°C and +20°C.

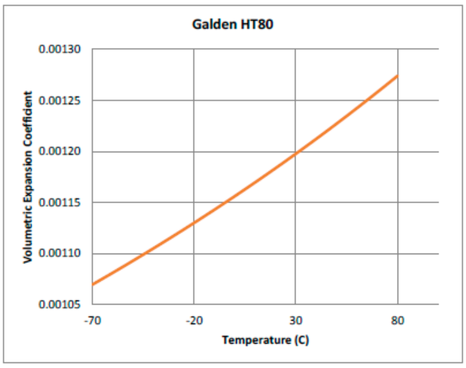


Figure 12a Thermal expansion coefficient of the selected hydraulic fluid Galden HT80.

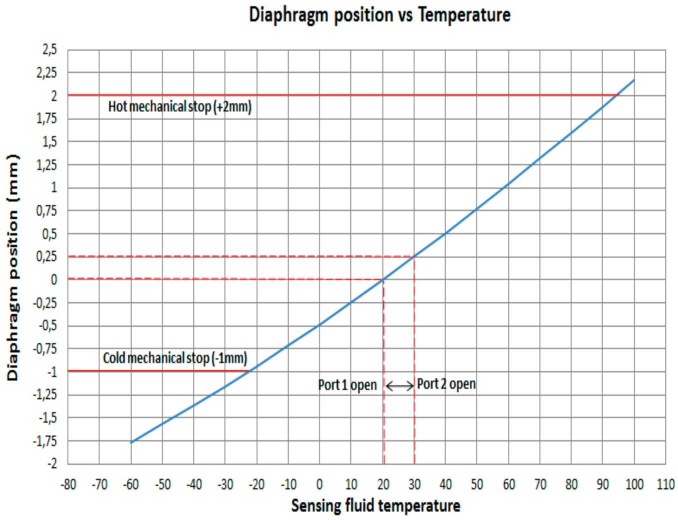


Figure 12b Valve switching points with sensing fluid temperature.

Since the initial EM design was unfortunately not functioning due to the high internal hydraulic pressures and a limited forces on the poppet the following internal modifications for EM (see Figure 14) were introduced:

- The titanium diaphragm was replaced by a machined titanium sheet to enhance actuation forces;
- The titanium poppet was replaced with a flexible PEEK version
- The hydraulic pressure was increased to +7 bars to enhance the actuation force on the poppet.

These modifications made the PBV design more robust for the passing fluid by handling higher hydraulic forces and larger pressure differences and improved closing-off of the ports at the extremes.

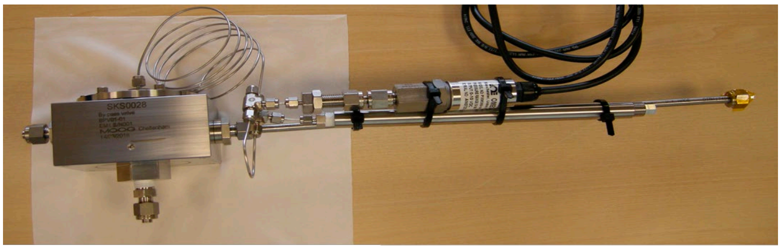


Figure 13 EM valve design. A pressure transducer (attached with tyraps to the entrance tube) is no part of the valve design but has been included in the hydraulic line for pressure sensing.

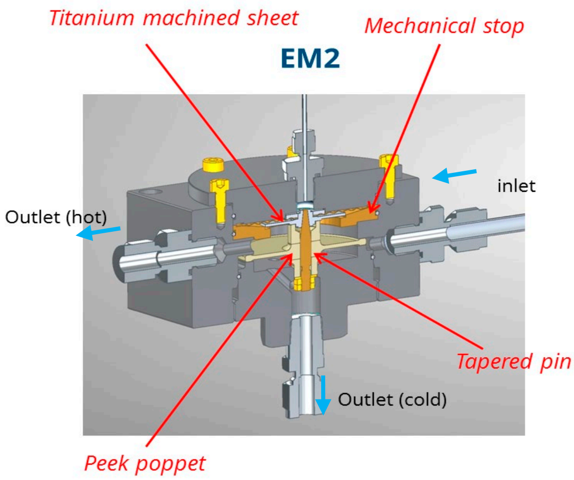


Figure 14 Modified PBV design. The diaphragm is introduced to enhance hydraulic forces and the PEEK poppet with Peek for more flexibility after closing of a port.

For the verification of the operations of the EM valve is integrated in two different test setups for performance testing in a single phase (MPL) and a two phase (LHP) cooling loop:

1. Mechanical Pumped Loop (MPL) set-up (section F)

2. Loop Heat Pipe (LHP) setup (Section G)

The setup and test results are briefly discussed in the following sections.

F. Single Phase Mechanical Pumped Loop (MPL) Test Setup

The MPL (Figure 15) consisted of a closed system with a laboratory pump (upper right corner), mainly made out of ¾" OD SS316 tube and a flexible SS316 bellows tube. For increasing and decreasing the operating temperature, two plate heat exchangers (HX1 & HX2) and a tube section with foil heaters were incorporated to simulate the payload.

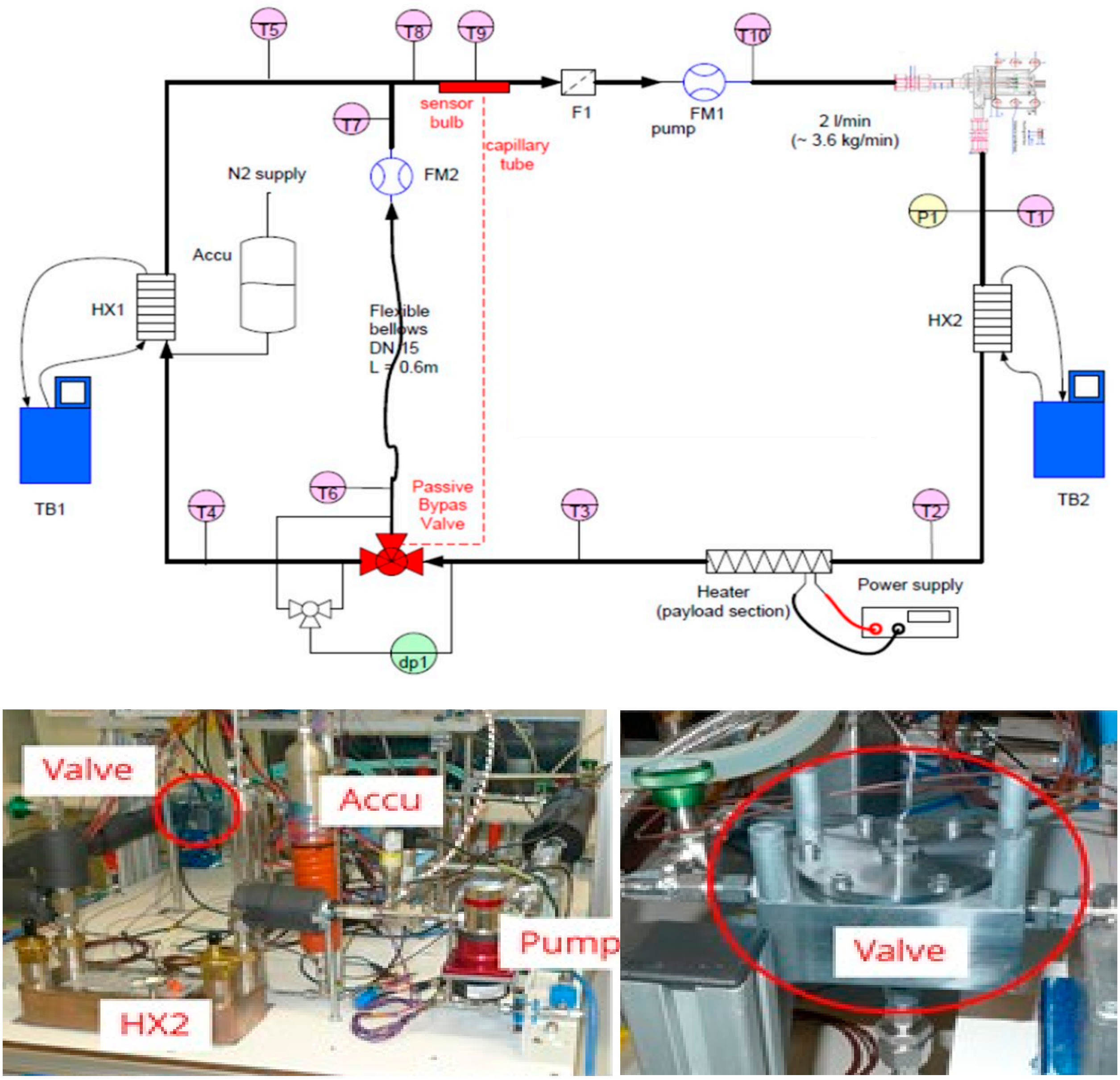


Figure 15 Setup of the EM-PBV integrated in a Mechanically Pumped Loop (MPL). Detail of the installed valve in vertical orientation (left lower photograph) during the operational Test.

For flow distribution measurement two mass flow meters were used, a flow meter (FM1) for total flow and the other one (FM2) for measuring the flow in the bypass branch. Pressure transducers were used for measuring the system pressure (P1) and the pressure drop (dP1) across the PBV. For compensating the thermal expansion of the liquid an accumulator is included. For the function verification tests (Figure 16) the sensor was detached from the tube and temperature controlled with a chiller while the liquid is pumped through the valve at ambient temperature.

For this the example (see Figure 16 for the valve tested in Z orientation) a COP@25^{0}C (definition in section B) was found having a switch range of ±10^{o}C with a small hysteresis of ±1.5^{0}C related to the thermal inertia of the hydraulic liquid (i.e. thermal response time) which puts constraints on the allowed temperature changes. However, for slowly varying thermal systems this shouldn't be an issue. For instance, for a control configuration test with the MPL, when slowly lowering the radiator temperature, the valve showed an excellent transient response. It nicely stabilized the flow distribution between the radiator and the bypass and at the same time stabilized the payload temperature around 17.5^{0}C @ 80% bypass flow, clearly demonstrating its autonomic regulating potential.

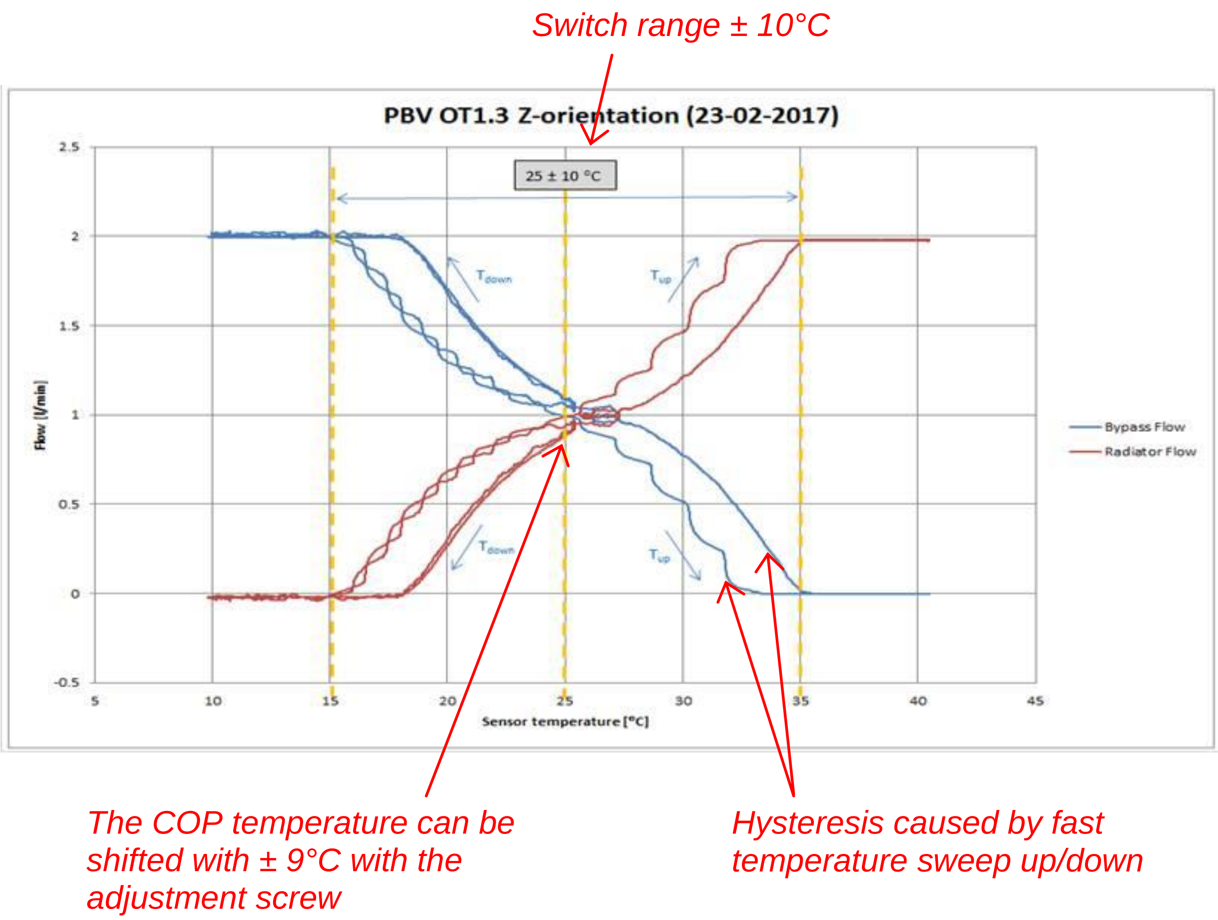


Figure 16 PBV tested in Z-orientation for a COP@25^{o}C. The hysteresis of ±1.5^{0}C between temperatures up end down is related to thermal inertia of the sensor bulb. The temperature slope is quite high at ±1^{0}C/min.

G. Two Phase (LHP) Test Setup

The LHP test setup (see Figure 17) is a modification of an existing dual Loop Heat Pipe loop System. One LHP has been used for the PBV performance tests. The setup is insulated to minimize the heat leak to the laboratory environment. See Figure 19 for a schematic picture of the LHP setup. After thorough cleaning of the EM valve, to prevent cross contamination, it has been installed in the LHP with two control valves V1 and V2 to bypass or actuate the Bypass Valve at will. Figure 18 indicates the difference in the LHP evaporator temperature between the two situations when lowering both the condenser (radiator) temperature and the heater power (load) The capillary across V2 is a safety measure to prevent liquid trapping (and subsequent pressure build-up) between the PBV and V2. The LHP loop is carefully filled with NH3 until the capillary action of the evaporator kicked in in the vale bypass mode. Total size of the setup was about 1.5 by 0.5 meter. A heater at the evaporator simulates the payload dissipation and the condenser is chilled with a thermostat bath simulates the radiator. The valve sensor bulb to control the bypass valve operations was located on to the evaporator.

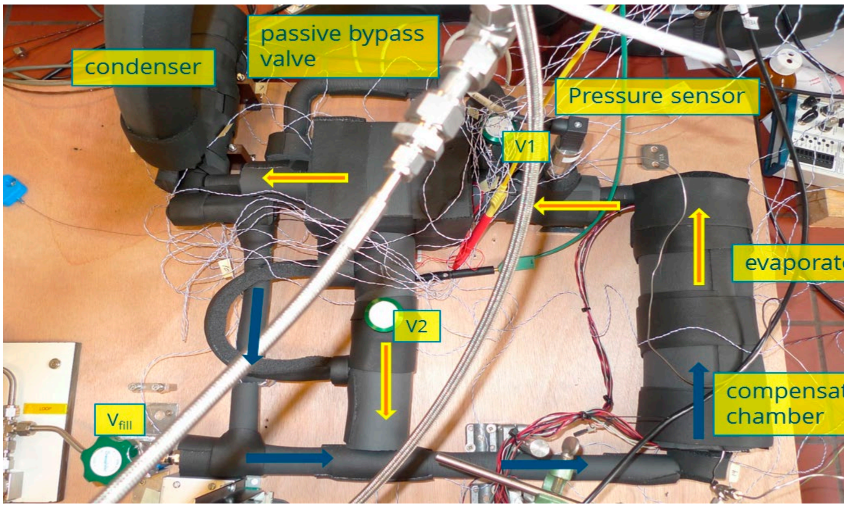


Figure 17 Test Setup (fully insulated) of the EM-PBV integrated in a Loop Heat Pipe system

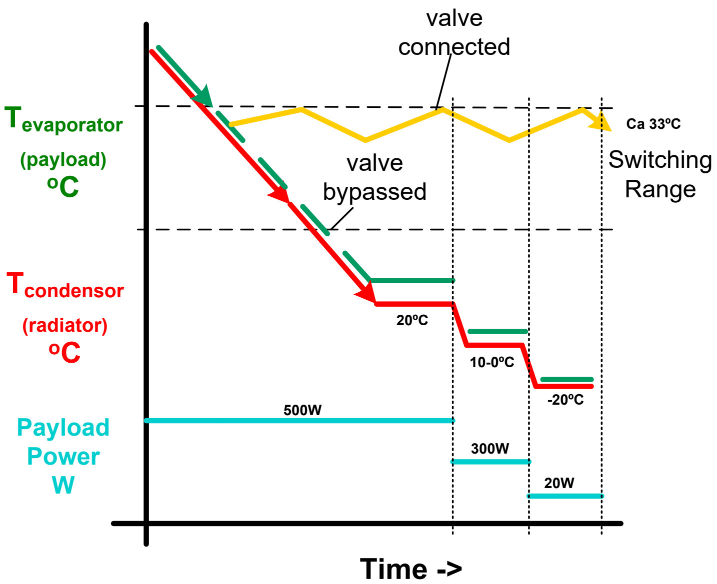


Figure 18 LHP Performance testing procedure with valve (orange line, V1=closed,V2=open) and without valve (green line, V1=open, V2=closed) while reducing the condenser temperature and load.

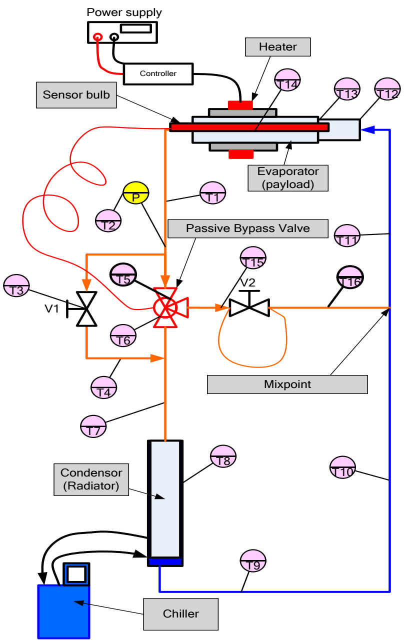


Figure 19 LHP Test Setup

For the general test sequence on the EM valve see Figure 18. For verification of the function of the valve a test was on the LHP with the valve bypassed and with the valve connected using combinations of V1 and V2. The general test sequences are conducted in a similar way for the valve bypassed (green dotted line) and connected (orange upper line). It started with an ambient condenser and evaporator temperature and a maximum load of 500W

The condenser temperature was reduced to 0°C and -20°C while reducing the load to 20W were the LHP just operates and then returned to the hot cases and back again to ambient conditions in gradual steps. See Figure 20 for the test conducted with the Passive Bypass Valve bypassed. As expected the evaporator (and sensor) temperature proportionally follows the condenser temperature and loads. At a condenser temperature of -20°C and a very small load of 20W the LHP starts to auto regulate (LHP switch off) around the laboratory temperature of 25°C. The V2 bypass was suspected but pinching the capillary tube did not influence the autoregulation/switch-off point. It has been reported[9,10] previously as typical LHP behaviour under <100W loads. After activating the PBV and repeating the test sequence (Figure 20) it is clearly visible that the PBV starts operating when the sensor temperature drops below 35°C. This is the theoretically expected upper temperature limit of the PBV with a Cross-Over-Point at 25°C and a switch range of ±10°C. When the bypass is slightly opened it allows a minimal flow of vapour to the mix point where it condenses and heats up the liquid going to the evaporator increasing/stabilising its temperature.

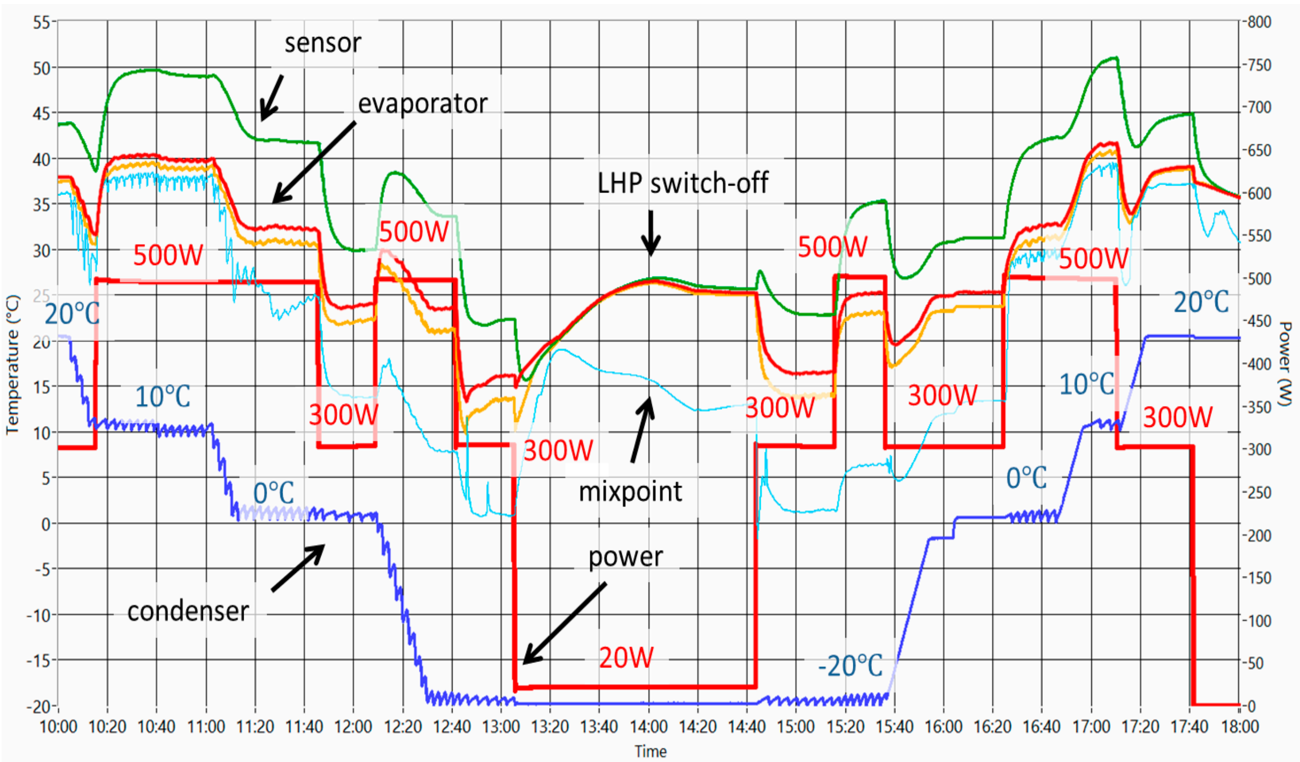


Figure 20 PBV LHP Performance Test results with PBV *bypassed* under decreasing & increasing condenser temperatures and loads. Autoregulation/switch-off around 20°C under small loads (<100W) has been reported before for other LHP systems tested in a laboratory environment.

Interestingly the PBV starts to oscillate (Figure 21) at a very low frequency (1 cycle per 2 minutes e.g. 4E-3Hz) which in most cases damps out within 15 minutes, achieving a stable operation after cooling down the condenser/radiator and reducing the load. This can probably be attributed to the relatively large thermal masses of evaporator heater blocks and the PBV itself. Furthermore the suboptimal thermal contact of the sensor to the evaporator heater worsens feedback response time. Even the autoregulation/LHP low power switch-off is more or the less stabilised by the valve at a frequency of about 1 cycle per half an hour e.g. @ 5E-4Hz). The valve operation stops when the sensor temperature increases above 35°C demonstrating the PBV control actions in a LHP.

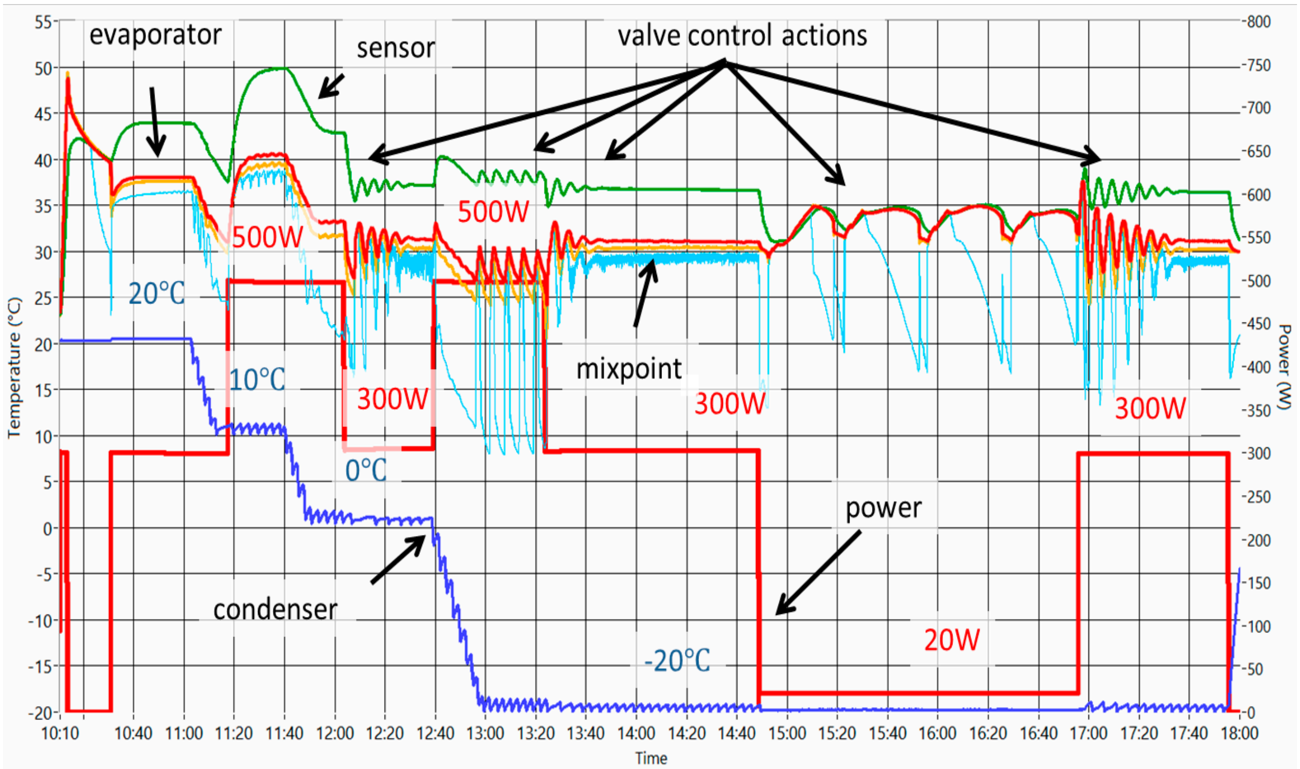


Figure 21 PBV LHP Performance Test results during the cooldown phase showing valve operations under decreasing condenser temperatures and loads. The heating up shows the same picture in reverse.

IV. Conclusion

The literature study patent survey revealed no problems related to IPR for the development of new Passive Bypass Valve concepts. A trade-off study was done for several variations of conceptual designs of the bypass valve. Technical requirements as well as system aspects were rated as well as breadboard testing was done for the most promising concepts. The hydraulically actuated thermostatic valve was selected for the design and manufacturing of the Engineering Model (EM) Passive Bypass valve. The EM valve is hydraulically actuated via capillary tube by expansion of a liquid (as function of temperature) inside a remotely located sensor.

The initial design based on a Titanium diaphragm failed to pass the performance test due to a lack of force. An internal modification of replaced the diaphragm with a machined Titanium sheet successfully increasing the force of the valve. The modified valve showed and excellent performance with an adjustable range of ±9°C (sensor screw) and repeatable switching range of ±10°C, in three orientations. A small hysteresis of ±1.5°C (when going quickly up or down in temperature) has been observed which could be related to the thermal inertia of the hydraulic liquid in the sensor bulb under fast temperature changes.

The two-phase LHP test showed that the PBV stabilized the (evaporator/payload) temperature around 33°±5°C (at the upper regulation limit) for a condenser temperature of -20°C and under varying load cases between 500W down to 20W.

With the performance demonstrated of the Engineering Model of the Passive Bypass Valve for single and two phase loop systems up to TRL4-5, the next step shall be the optimization and qualification (QM/FM) of valve designs for dedicated aerospace applications up to TRL 6.

Design recommendations:

- Since the EM design is very robust, a significant mass reduction is possible by removing access material. Expected weight for a stainless steel body (316L) is 750g and for titanium body is 550g.
- The switch range can be narrowed (for an increased temperature sensitivity) by enlarging the sensor housing (i.e. more hydraulic liquid for enhancement of the thermal expansion) at the cost of an overall mass increase of the sensor.

- Attachment of the sensor bulb to the payload should be improved, resulting in a enhanced thermal contact and hence better feedback response time, with less oscillations.
- To avoid possible leaks and enhance life time, valves and hydraulic couplings should be removed from the capillary system.
- Delete the adjustment screw from the sensor, which is a potential leak source. It can be considered to fill the sensor when the PBV is installed in an MPL. In this case to the flow distribution can be directly verified while changing the fill rate.
- For some applications, to avoid total blocking of a port, a small leakage can be introduced by drilling small holes in the poppet.

Acknowledgments

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