Europa Clipper Passive Thermal Control Valve Test and Analysis

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The Europa Clipper spacecraft utilizes passive thermal control valves (TCV) in an active thermal control system to maintain spacecraft component temperatures within their allowable limits. The single-phase mechanically pumped fluid loop (MPFL) recovers heat dissipated from the electronics and uses it to maintain the propulsion system warm. When the heat dissipated by the electronic boxes is in excess of what is required to maintain the spacecraft within its maximum allowable temperature limits the mixing valves open and direct flow in the MPFL to the radiator to reject this excess heat. The loop uses two mixing TCVs placed in series to modulate flow in the radiator from a maximum of 0.16% when the valve outlet temperature is <4 ºC to a minimum of 92% when the valve outlet temperature is >24 ºC. Each heritage thermal control valve has the capability to reduce flow to the radiator to 4% of the total flow rate. Thus using two TCVs in series should reduce the total flow to the radiator to 0.16% (4% of 4%). This paper describes the thermal and hydraulic test results for Europa Clipper engineering model (EM) mixing valves. For the first time two heritage mixing valves previously developed for the Mars Science Laboratory (MSL) project were packaged in series to modulate flow to the radiator from 0.1% to 95% of full flow between temperature range of 4 ºC to 24 ºC. Individually, each mixing valve was able to modulate the flow from 2% to 96% of full flow between the same temperatures. Pressure drop was measured between 1.5 to 3 psid (10.3 to 20.7 kPa) depending on the temperature of the mixed fluid and the opening fraction of the valves. A methodology was developed, tested, and validated to adjust the setpoints with an accuracy of 0.1 ºC. The measured flow splits were corrected for the effects of impedance due to the flow meters used to measure the flow rates. Finally, cold inlet flow rate (radiator flow in flight) increased linearly as a function of mixed (or outlet) temperature for individual valves which translated to parabolic increase in flow rate with temperature for the configuration with two mixing valves in series.

Nomenclature

CFC-11	=	*Trichlorofluoromethane (R-11)*
ΔP	=	*Pressure difference (PSID)*
ECIPA	=	*Europa Clipper Integrated Pump Assembly*
EM	=	*Engineering Model*
HRS	=	*Heat redistribution System*
LPM	=	*Liters per minute*
MSL	=	*Mars Science Laboratory*
PM	=	*Propulsion Module*
REM	=	*Rocket Engine Module*
RF	=	*Radio Frequency*
RHB	=	*Replacement Heater Block*
TCV	=	*Thermal Control Valve*

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$\dot{V}$ = *Volumetric Flow Rate (m^3/s)*
WCC/H = *Worst Case Cold/Hot*

I. Introduction

Europa Clipper is a deep space planetary exploration mission with the objective of evaluating the potential habitability of Jupiter's icy moon Europa. It aims to (i) characterize the icy shell of Europa and the properties of the subsurface water including ocean salinity and ice sheet thickness, (ii) determine the chemical composition of the surface matter and the atmosphere including potential plumes, and (iii) characterize the geology of the moon to aid with the selection of future landing sites as well as to understand the formation of magmatic, tectonic, and impact landforms [1]. Various robotic planetary exploration missions such as the Mars Pathfinder, Mars Exploration Rover, and Mars Science Laboratory spacecraft and rovers have used mechanically pumped fluid loops (MPFL) for thermal control. The Europa Clipper spacecraft utilizes a MPFL to maintain component temperatures within their allowable limits [2]. The primary constituents of the fluid loop are a centrifugal pump, passively actuated thermal control valves, various aluminum heat exchanging tubes, and stainless-steel transfer tubes to move the CFC-11 fluid around the spacecraft. The purpose of this heat redistribution system (HRS) is to absorb heat dissipated by the electronic boxes and reject it to space or transfer it to other parts of the spacecraft. Specifically, the heat is used to maintain propulsion module components' temperatures within their specified limits including the propellant tanks, the reaction control system thrusters, reaction wheel units and propellant lines and valves. The spacecraft is designed to operate between 0.65 AU and 5.6 AU where the solar flux varies from 3300 W/m^2 to 49 W/m^2. The spacecraft avionics, power conditioner and distribution system, and RF components also dissipate approximately 350 W. When the heat recovered by the HRS exceeds the spacecraft needs the excess heat is rejected out of the radiator. The spacecraft is designed to

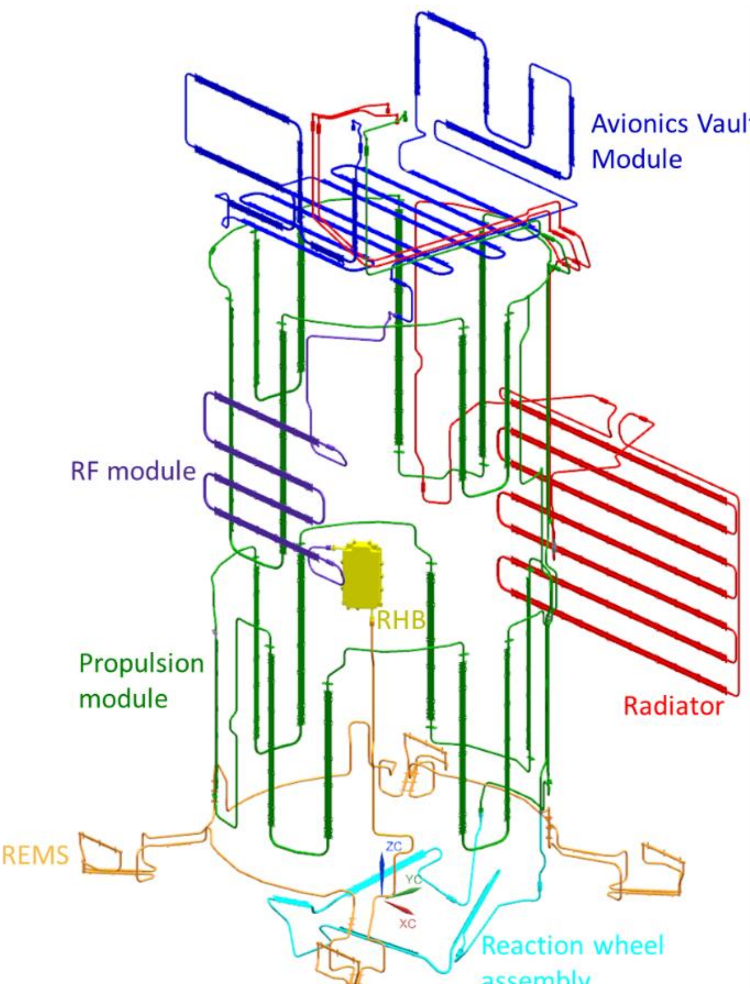

Figure 1: Europa Clipper spacecraft HRS tube layout.

modulate heat rejection out the radiator from 10 W when orbiting Jupiter to 350 W during the closest approach to the Sun and during Europa flybys when all the instruments and their electronic boxes are turned on to collect data. To achieve this heat loss modulation the HRS uses a fluid loop with two passive thermal control valves (TCV) placed in series to throttle fluid flow to the radiator and low temperature Louvers mounted on the radiator panel. The TCVs used for Europa Clipper HRS were initially developed during the Mars Pathfinder program [3] and updated for the Mars Exploration Rover [4] and Mars Science Laboratory [5] missions. The TCV is a three-way valve that uses an oil filled actuator to modulate flow coming from each of the two inlets between 4% and 96% of the total flow over a temperature range of 20 ºC [6]. The heritage thermal control valves do not have the ability to fully shut off the flow to the radiator, instead they restrict flow to the shut off port to 4% of the total flow rate. The 4% flow through the radiator leads to a heat loss from the radiator of 39 W. This heat loss can be reduced further if the radiator flow can be throttled to <0.3% of the total flow rate of 1.5 LPM. Fluid thermal analysis showed that two mixing valves in series can achieve flow rate to the radiator of 0.16% of full flow with both mixing valves in fully shut state [7]. The use of two mixing valves in series should reduce spacecraft heat loss through the radiator by 30 W.

To demonstrate the minimum flow rate through two mixing valves in series an engineering model (EM) TCV assembly was procured with two mixing valves placed in series to measure the flow rate through the cold port (flight radiator port) as a function of mixed fluid temperature. The mixing valves in the EM TCV assembly were tested individually as well as assembled in series using the system working fluid CFC-11.

II. Background

Figure 1 shows Europa Clipper spacecraft HRS layout consisting of 110 m of tubing including 53 m of tubing used for transferring heat in or out of the fluid. The remainder of the tubing is used for transporting the fluid throughout the spacecraft. The latter can be divided into the avionics vault module, the RF module, the propulsion module (PM), the rocket engine modules (REMs), the replacement heater block (RHB), the reaction wheel assembly (RWA), and the radiator. The two purposes of HRS are (1) to reject heat out of the radiator if there is excessive heat dissipated in the spacecraft and (2) to absorb heat from electronics boxes located in the vault and RF modules and distribute them to the PM, the RWA, and the REMs. The flow to the radiator and therefore heat-rejection out of the radiator is controlled by the thermal control valves. When the spacecraft is cold the flow bypasses the radiator reducing heat loss from the radiator thus conserving power. As the spacecraft heat dissipation increases the thermal control valves direct larger fraction of the total fluid flow to the radiator thus increasing heat loss from the spacecraft. Finally, the RHB is used to supplement heat to the loop in case the vault and RF modules do not dissipate sufficient heat to maintain propulsion components above their allowable temperature limits.

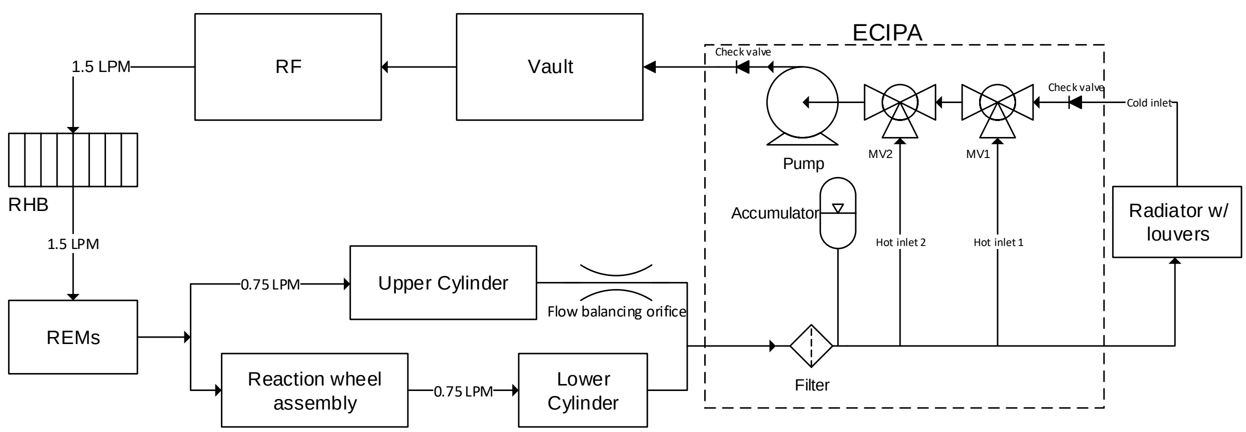

Figure 2: Europa Clipper HRS loop diagram showing major system components and modules.

As previously stated, the thermal control valves play a very important role in managing the heat loss from the spacecraft. Figure 2 shows Europa Clipper HRS diagram including the two mixing valves placed in series to throttle the flow rate to the radiator to <0.16% of the total system flow rate. Table 1 shows the flow partitioning requirements of the mixing valve assembly as a function of temperature. The requirements state that TCV cold inlet flow fraction shall be <0.16% of total flow rate when the valve outlet fluid temperature is <4 ºC. The latter is set based on MON3 oxidizer freeze point of -15 ºC. Flow to the radiator must increase monotonically between 4 and 24 ºC. The cold inlet flow fraction must be larger than 92% when the valve outlet temperature is ≥ 24 ºC to ensure the fluid is cooled by the radiator and the thermal control system can maintain the batteries below their allowable temperature of 30 ºC.

Table 1: Europa Clipper thermal control valve specifications.

Valve Outlet Temperature (ºC)	Hot inlets (bypassing Radiator) (%)	Cold inlet (from Radiator) (%)
≤ 4 ºC	>99.7%	≤0.16%
20 C delta between low and high temps	Monotonic increase in flow % with increasing temperature	Monotonic decrease in flow % with increasing temperature
≥ 24 ºC	<8%	>92%

The TCV functions based on passively controlled actuators identical to those used in the MSL and M2020 rovers. The passively actuated valves have proved to be highly reliable over thousands of cycles on the Martian surface in MSL's Curiosity rover. The valves are also compatible with the CFC-11 working fluid and work in the temperature range between -35 ºC and 70 ºC. The mixing valve actuator position is determined based on the mixed fluid temperature exiting the valve. Figure 3 shows a schematic of the two mixing valves in series with the cold inlet port and the mixed outlet port shown. Note, the two hot inlets are not shown in this cross-sectional view. Figure 3 also shows the passive actuator and the spool that proportions the flow between the two inlets of each valve. The mixing valve open/close set points are adjusted by adding spacers between the housing and the actuator to displace the spool relative to the inlets at a given temperature.

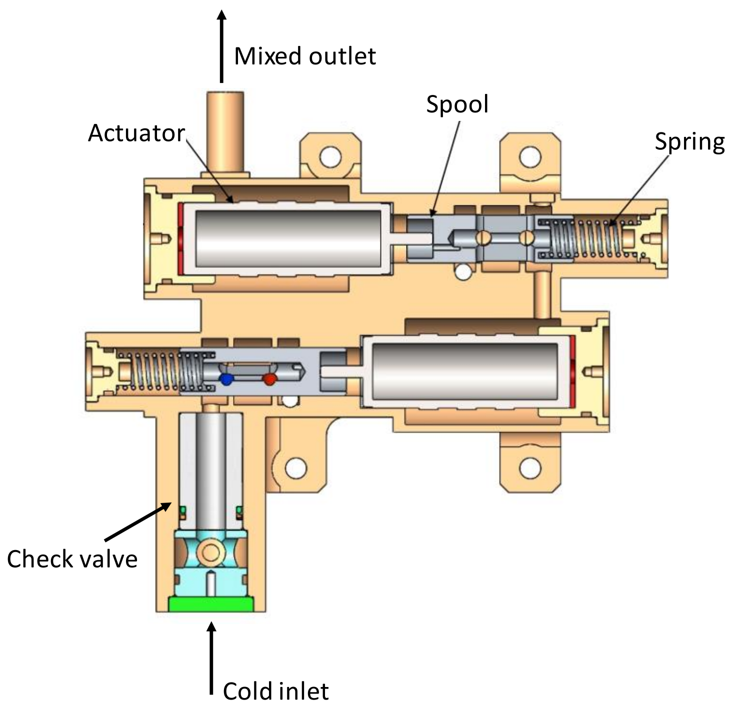

Figure 3: Europa Clipper flight thermal control valve configuration showing two mixing valves in series. Note: the two hot inlets are not shown in this cross-sectional view.

Figure 3 shows the engineering model mixing valve assembly containing two mixing valves configured in series. The two mixing valves are identical and feature the same open and close set-points. Key data when designing thermal control of the system is the knowledge of flow rate in each inlet port as a function of valve outlet flow temperature (mixed flow temperature).

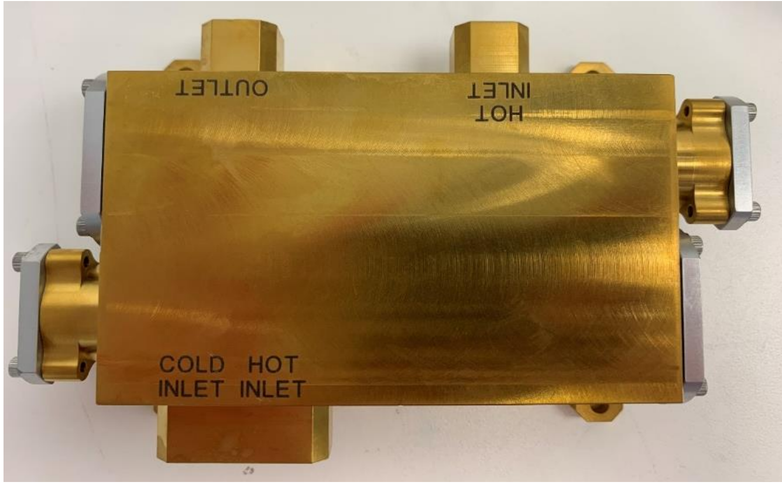

Figure 4: Europa Clipper engineering model thermal control valve.

III. Thermal control valve testing

A test fluid loop was built to measure the flow through each of the mixing valve branches as well as the pressure drop between each inlet port and the outlet port. For all tests all fluid in the loop was at a constant temperature, i.e., both hot inlets and the cold inlet had the same temperature. The hot inlet 1 and cold inlet flow rates were measured in addition to total flow. Hot inlet 2 was calculated as $\dot{V}_{hot2} = \dot{V}_{total} - \dot{V}_{hot1} - \dot{V}_{cold}$. The fluid temperature was varied between 0 ºC and 25 ºC using an air to liquid heat exchanger. The test loop was placed in a GN2 filled chamber and the temperature of the chamber was varied. The flow meters presented a large impedance in the split flow branches that affected the flow split in the mixing valve. Impedance of each inlet of the mixing valve was estimated based on

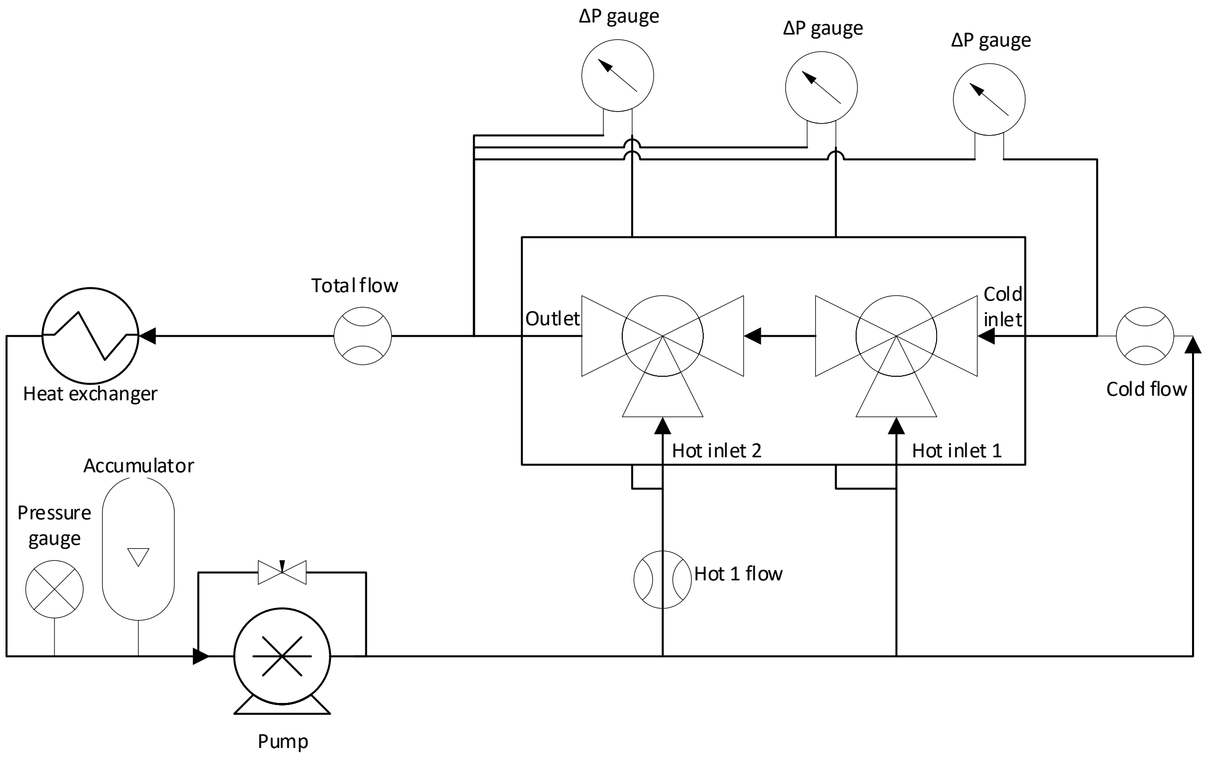

Figure 5: Thermal control valve test loop diagram.

the measured flow rate and pressure drop. Then, the flow fraction for each inlet port was corrected to eliminate the effects of flow meters in the path (see Appendix).

Figure 6 shows the corrected flow fraction at each of the inlets in the EM mixing valve test. At temperatures <4 ºC the cold inlet flow fraction was less than 0.16% (flow meter lower calibration limit) while the two hot inlets featured the balance of the flow. The hot inlet flow fraction begins decreasing at 4 ºC feeding the second mixing valve (MV2). The cold inlet (radiator flow) flow fraction exceeds the fully closed requirement of 0.16% at 5.5 ºC. Between 5.5 and 24 ºC the cold flow fraction increases monotonically to reach 98% at 25 ºC. Note the measured flow fraction at 25 ºC was 93.7% without considering correction for the flow meter impedance. Both the fully open and fully shut off flow fraction in the cold inlet meet the requirements for Europa Clipper fluid loop thermal control. Additionally, the maximum flow fraction in the cold inlet will not be 98% of full flow due to the presence of large impedance in the HRS radiator. The latter accounts for 5 psid (34.5 kPa) pressure drop at 1.5 LPM of CFC-11 at average temperature of -15 ºC.

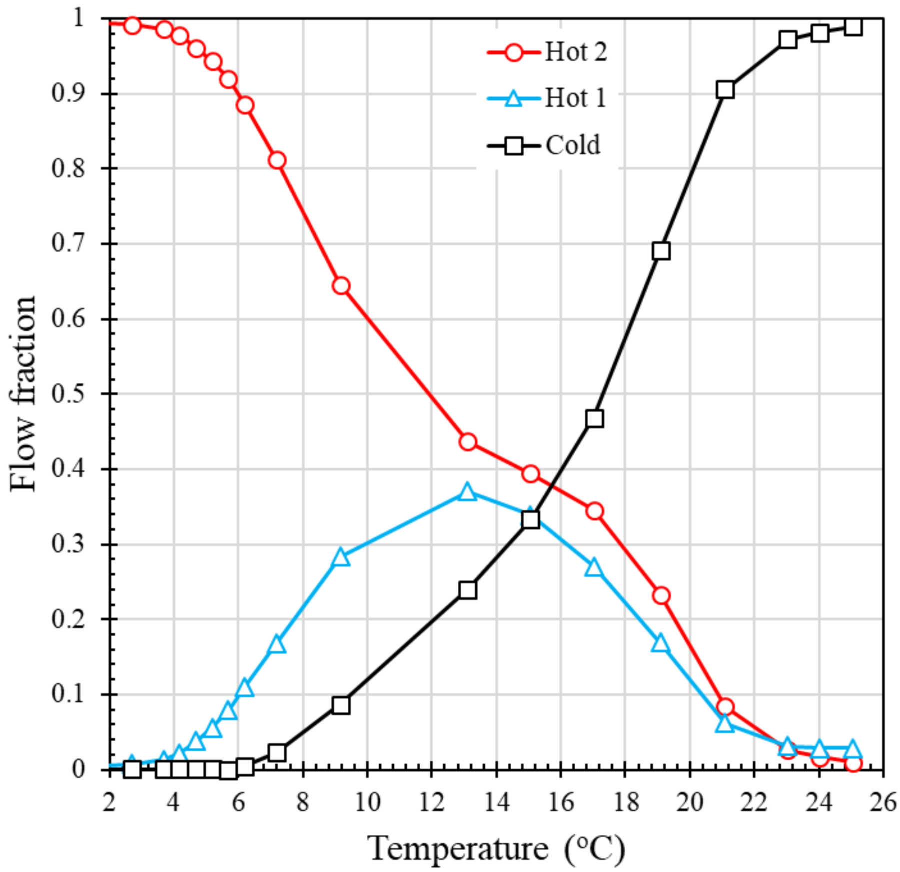

Figure 6: Flow fraction of hot 1, hot 2, and cold inlets of the thermal control valve as a function of mixed fluid temperature.

One of the challenges configuring two mixing valves in series is the verification of the setpoints of the individual mixing valves. Each mixing valve has a unique shimming based on the actual dimensions of the parts that go into assembling that valve. Two tests were performed to verify the open/closed setpoints of each valve. This was performed by installing the first valve in the mixing valve housing and testing it for the close/open setpoints followed by removing the first mixing valve and installing the second mixing valve and repeating the test. Individually, the mixing valves had a minimum leak rate through the cold port of 2% at 4 ºC and a maximum flow fraction of 97% at mixed temperature >24 ºC.

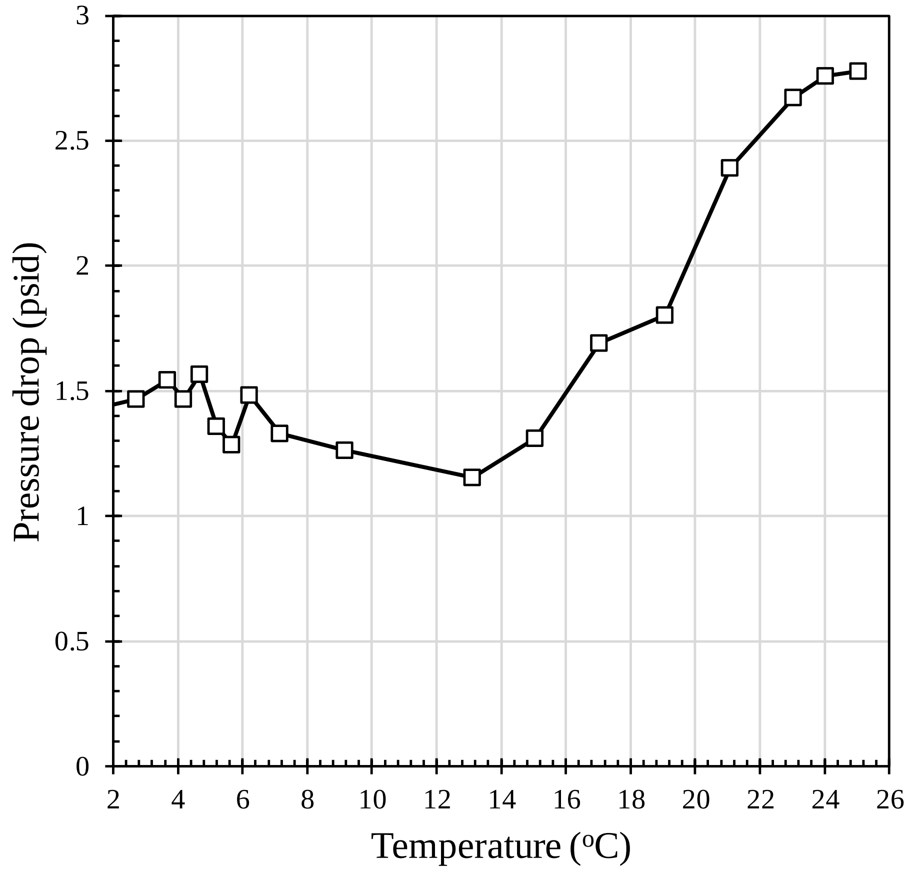

Figure 7: Pressure drop of thermal control valve as a function of mixed fluid temperature.

Figure 7 shows pressure drop through the TCV as a function of mixed fluid temperature. Pressure drop through the TCV was dependent on the mixing valve spool position and mixed fluid temperature. Indeed, at cold temperatures majority of the fluid flows through hot 2 inlet and therefore most of the fluid flows through only one mixing valve and the pressure drop is approximately 1.3-1.6 psid (9-18 kPa). At higher temperatures, majority of the fluid flows through the cold inlet and therefore two mixing valves and the pressure drop through the valve assembly can reach up to 2.8 psid (19.3 kPa). Note that implicit in the data is also the additional effect of changes in fluid viscosity and density as a function of temperature. The measured pressure drop here is consistent with the 1.5 psid (10.3 kPa) pressure drop through each mixing valve reported by Birur et al. [6] for MSL.

IV. Conclusion

Two MSL like mixing valves in series were selected for use in Europa Clipper HRS thermal control. An engineering model was tested and its performance compared to the requirements. The tested mixing valve met the fully shut off and fully open requirements of the Clipper fluid loop. The thermal control system designed with this mixing valve should be able to minimize heat loss from the radiator to 10W during Jupiter orbit and reject up to 350W during Europa flybys. Pressure drop through the mixing valve varied between 1.5 psid (10.3 kPa) and 2.8 psid (19.3 kPa) depending on the mixed fluid temperature. This was consistent with previous pressure drop data obtained for MSL and M2020.

Acknowledgments

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Appendix

ΔP_1, ΔP_2, and ΔP_3 are the measured pressure drop across hot 1, hot 2, and cold inlets. $\dot{V}_1$, $\dot{V}_2$, and $\dot{V}_3$ are measured flow rates. With no flow meters in the test setup the variables corrected for the effects of flow meter impedance are denoted as $\Delta P_1'$, $\Delta P_2'$, $\Delta P_3'$, $\dot{V}_1'$, $\dot{V}_2'$, $\dot{V}_3'$, respectively.

At steady-state pressure drop in all branches will be equal if there was no additional impedance due to the flow meter and only the valve impedance controlled the flow split.

$$\Delta P_1' = \Delta P_2' = \Delta P_3'$$

Additionally, by continuity

$$V_{total} = \dot{V}_1' + \dot{V}_2' + \dot{V}_3' = \dot{V}_1 + \dot{V}_2 + \dot{V}_3$$

The measured impedance of each branch can be defined as $R_x = \Delta P_x / \dot{V}_x^{\,2}$.

Combining the three equations we can solve for flow fraction of each branch as a function of measured parameters. The corrected flow fraction of cold inlet is then

$$f_{cold} = \frac{\dot{V}_3'}{V_{total}} = \frac{1}{2}\left[\left(\frac{2R_1^2}{R_1^{3/2}R_3^{1/2}} + \frac{R_2^2}{R_1^2} + \frac{R_2^2}{R_1 R_3} + \frac{4R_2}{R_1}\right)^{1/2} - \frac{R_2}{\sqrt{R_1 R_3}} - \frac{R_2}{R_1}\right]$$

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